Economic and carbon emissions model for controlled traffic farming in vegetables

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Horticulture Australia Project Number: VG09019 (September, 2011)

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This is the final report of the above project. It covers the conduct and results of the project in detail, and also includes media and technical summaries.

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Controlled traffic farming (CTF) keeps all paddock traffic in the same wheel tracks year after year. The basis of CTF is simple - plants grow better in soft soil, wheels work better on roads. CTF offers many benefits, including reduced soil degradation and energy and fertiliser use (leading to lower greenhouse gas (GHG) emissions), and improved water use efficiency, crop productivity and timeliness of cropping operations.

Although a simple concept, many issues need to be addressed before CTF is a commercially viable option in the vegetable industry, particularly in Tasmania, with its diversity of crops, mechanisation and topography. Project VG07058 (Controlled traffic farming systems for the Tasmanian vegetable industry) highlighted the need for a better understanding of the economics of CTF. This project developed farm economic and GHG models relevant to different enterprise types in the Tasmanian vegetable industry. The models allow variables to be altered to conduct sensitivity analyses, thereby identifying the factors that are most important in delivering the benefits of CTF. This helps identify areas of focus for the adoption of CTF, and for future research and development.

Modeling showed CTF could increase average Gross Margin across the rotation by 66%, while seasonal controlled traffic farming (SCTF) could lead to a 16% increase, compared to the conventional production system. Under the same scenario, return on investment in plant and machinery could improve by 150% with the use of CTF and 35% with SCTF. These results were obtained for a north-west coast vegetable farm in Tasmania. Modeling for a midlands farm showed similar responses.

On an industry-wide basis, controlled traffic has the potential to increase the vegetable industry farm gate gross return by an amount ranging from $11 – 29 million annually, equivalent to an increase of 13% – 29% over present estimates.

An additional component of the model showed that controlled traffic has significant potential to reduce greenhouse gas emissions, particularly in relation to nitrous oxide generation. There are many unknowns in this field of work, and the results of the model indicate the potential of the system, rather than a definitive assessment of actual emissions levels.

Future efforts should focus on engaging industry and growers in getting a better understanding of the economic potential of controlled traffic in order to encourage greater collaboration and adoption.

Technical Summary

Project VG09019 - Economic and carbon emissions model for controlled traffic farming in vegetables

Interest in controlled traffic farming (CTF) in the Tasmanian vegetable industry has increased rapidly in recent years. CTF keeps all paddock traffic in the same wheel tracks year after year. The concept is simple - plants grow better in soft soil, wheels work better on roads. CTF offers many potential benefits, including reduced soil degradation and energy and fertiliser use (leading to lower greenhouse gas (GHG) emissions), and improved water use efficiency, crop productivity and timeliness of cropping operations.

There are many technical issues to be addressed before CTF is a commercially viable option in the vegetable industry, not least of which is the modification of machinery to allow integration of compatible track and working widths. Such changes come at a cost, and project VG07058 (Controlled traffic farming systems for the Tasmanian vegetable industry) highlighted the need for a better understanding of the economic costs and benefits associated with CTF. This project developed a series of farm economic and GHG models relevant to different enterprise types in the Tasmanian vegetable industry. A feature of the models is the capacity to easily alter input variables in order to conduct sensitivity analyses, thereby identifying those factors that are most important in delivering the benefits of CTF. This is useful for growers to determine the key areas of investment, and also researchers and funding bodies to identify aspects of CTF that require further investigation.

Economic analyses were done for both fully integrated CTF and seasonal controlled traffic farming (SCTF). SCTF accepts random traffic at harvest, on account of the current difficulty of incorporating harvesters into the system. Compacted wheel tracks are retained with the use of satellite guidance and common track and working widths of all equipment used up to harvest. The compaction effects of harvest traffic are subsequently managed with tillage in the crop growth zone, with guidance allowing the benefits of compacted tracks to be retained.

Economic modeling showed that a scenario considered to be “achievable” under CTF could increase average Gross Margin across the rotation by 66%, while a partial transition to seasonal controlled traffic farming (SCTF) could lead to a 16% increase, compared to the current conventional production system. Under the same scenario, return on investment in plant and machinery could improve by 150% with the use of CTF and 35% with SCTF. Smaller tractors help reduce machinery capital costs for controlled traffic, although these are somewhat offset by the cost of guidance and equipment modification. Depending on a number of factors, equipment investment could reduce by 35% for a fully integrated controlled traffic system. These results were obtained for a north-west coast vegetable farm in Tasmania. Modeling for a midlands farm showed similar responses.

The principles and benefits of CTF are well documented, but there are a number of technological barriers to widespread adoption in the vegetable industry. There is a perception that the changes required to achieve a compatible machinery suite are too difficult to overcome. However, modeling shows that the industry as whole could gain significantly from the change, and the potential economic improvement could well justify the cost of change. Based on the returns calculated by the model, controlled traffic has the potential to increase the vegetable industry gross return at the farm gate by an amount ranging from $11 – 29 million annually, equivalent to an increase of 13% – 29% over present estimates.

An additional component of the model showed that controlled traffic has significant potential to reduce greenhouse gas emissions, particularly as a result of the impact that improved soil structural conditions has on reducing nitrous oxide generation. The model indicated farm-based emissions could reduce by 26% for seasonal controlled traffic, and 60% for controlled traffic, a combination of reduced fuel use (reduced tractor power and working time) and lower nitrous oxide emissions. There are many unknowns in this field of work, and the results of the model indicate the potential of the system, rather than a definitive assessment of actual emissions levels.

The focus of future work in the vegetable industry should be on supporting adoption of controlled traffic, in part through wider dissemination of the results developed in this project. The economic model will be used in controlled traffic related extension activities over coming months.

1. 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 due to improved trafficability on permanent compacted wheel lanes. There is a wide range of evidence that CTF improves profitability, and growing evidence that significant reductions in greenhouse gas emissions (GHG) can be achieved through the adoption of CTF.

Project VG07058 (Controlled traffic farming systems for the Tasmanian vegetable industry) highlighted the diverse range of equipment used in the vegetable industry. This complicates the objective of having distinct and permanently separated traffic and crop zones, which is the basis of CTF. The same project also indicated the need for a better understanding of the economic costs and benefits associated with CTF. While the modification, or replacement, of equipment to achieve compatibility is an upfront expense, improved returns should make the investment worthwhile. Understanding the costs and benefits is important for the progress of CTF adoption.

Another aspect of controlled traffic which is attracting attention is the capacity to reduce greenhouse gas emissions during the crop production phase. The lower energy use of CTF has an immediate impact, but there are many inter-related aspects which influence the GHG emissions from fertilisers and the soil.

This project was undertaken in an effort to better understand and predict the economic benefits arising from adoption of controlled traffic. The best "real life" assessment of this would be through the study of enterprises before and after conversion to CTF. However, the development of CTF in the vegetable industry is in its very early stages, and there are no case studies on which to draw for such an assessment. Furthermore, several case studies would be required from diverse operating environments in order to generate a sufficiently broad base of information.

The alternative is to model the impact of the changes. Gross margin models are well developed for the vegetable industry in Tasmania, and this provided a sound basis on which to build a new model with the capacity to incorporate the changes that are likely to occur with a transition to CTF.

As an add-on to the economics model, a simple model component was added in an effort to estimate how GHG emissions might change under a CTF production scenario. This proved to be more complicated than initially envisaged, and while the model provides some indicators of potential changes to GHG emissions, it is actually more useful in identifying the areas in which knowledge is lacking, and which could be the focus of future research.

As part of this project, literature reviews were done covering three topics:

- economics of CTF
- the impact of CTF on greenhouse gas emissions
- approaches to modelling GHG emissions to allow comparison of different farming systems

The results of the literature reviews are given in more detail in the following section. In summary, the reviews indicated:

- The adoption of CTF can provide significant economic benefit through improved yield and reduced capital and operating costs
- Very little research is reported in the literature on the impact of CTF on greenhouse gas emissions. However, research has identified that soil conditions commonly associated with conventional production systems increase GHG emissions, so by inference, soil GHG emissions should reduce under CTF. Further, reductions in fuel use provide a direct reduction in GHG emissions.
- GHG models range from the simple to the complex. Simple models are based on "standard" production methods and industry standard emissions factors. They do not lend themselves to analysis of significant changes to the production system. On the other hand, complex models require an extensive amount of information on soil conditions and cropping cycles, which were beyond the capabilities of this project to integrate with the economic model.

The principles and benefits of CTF are well documented, but there are a number of technological barriers to widespread adoption in the vegetable industry. There is a perception that the changes required to achieve a compatible machinery suite are too difficult to overcome. However, economic modeling conducted in this project showed that the adoption of CTF could provide significant economic benefits both at the individual farm level, and on an industry-wide basis.

An additional component of the model showed that controlled traffic has significant potential to reduce greenhouse gas emissions, particularly as a result of the impact that improved soil structural conditions has on reducing nitrous oxide generation. Lower fuel use, due to reduced tractor power and working time, also contributes to the lower GHG emission levels. There are many unknowns in this field of work, and the results of the model indicate the potential of the system, rather than a definitive assessment of actual emissions levels.

2. Literature reviews

Three literature reviews were conducted as part of this project, covering the topics of economics and controlled traffic farming, the impact of controlled traffic on greenhouse gas emissions, and greenhouse gas models.

2.1 Economics of controlled traffic farming

The commercial uptake of CTF in the Australian grain industry has been largely grower driven. Once the necessary 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. The adoption of CTF also allows the capture of a number of system effects, such as improved timeliness, which further complicate side-by-side comparisons (Tullberg, 2010). Consequently, economic analyses of conversion to CTF are rare, have generally been performed after the event, and have been limited by the quality of historical data.

An early Australian study of the economics of CTF in grain production showed that conversion to CTF would produce internal rates of return (IRR) ranging from 13.5% to 18.9%, based on a number variables such as savings/ha and discount rate (Bright and Murray, 1990). Another early study involved the modelling of UK grain cropping systems using different conventional and zero traffic management approaches and differing inventories of machinery (Chamen and Audsley, 1993). It was estimated that unpowered tillage equipment used in controlled traffic would be 35% cheaper than conventional system equivalents, due to reductions in draft load arising from better soil conditions, which in turn, could lead to equipment of lighter construction. The CTF systems modelled in this study relied on yield increases to maintain profitability.

While not an economics study as such, a 17% increase in the marketable yield of potatoes was reported in Scottish controlled traffic experiments (Dickson *et al.*, 1992). It was also noted there were 30% more clods recovered at harvest under conventional traffic systems, which clearly impacts harvest efficiency, and post-harvest tillage of conventionally trafficked areas required 70% greater draft force, adding a great cost to the conventional production system. Although the average gross margins for potatoes favoured controlled traffic, the 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). Analysis for other crops in the rotation showed significant improvements for the controlled traffic system, with spring barley, winter barley and oil seed rape gross margins being 23%, 35% and 42% higher than conventional traffic systems, respectively.

Operating and capital cost savings were indicated for CTF in irrigated grain crops in a tropical environment (McPhee *et al.*, 1995). Significant reductions were recorded for both total and peak tillage power requirements. When applied to machinery investment decisions, these reductions indicated a 69% reduction in capital cost (smaller tractors), a 71% reduction in operating costs, and a 73% reduction in total costs. The benefits of the system extended beyond reductions in power requirements. Improved timeliness allowed more frequent and more reliable crop production, further enhancing the economics of the system.

Analysis of a Darling Downs (Queensland) grain cropping group showed increased cropping frequency, increased yield and improved grain prices (due to greater yield reliability in dry years when prices are higher) have the potential to improve gross income by 44% (Bowman, 2008). Using historical data from group members, the analysis showed a 17% Return on Capital for individual members of the group. The combined benefits of the CTF system have the potential to nearly double the business profit level for group members.

A whole farm 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 and quality improvements, and input reductions (Kingwell and Fuchsbichler, 2011). Sensitivity analyses showed that the major contributor to the increased profit was increased yield.

The experiences in the Australian grain industry have been applied on the Chinese Loess Plateau, an area dominated by winter wheat production grown on summer fallow stored soil moisture. Seven years of field trials showed a profit increase of 28% for wheat produced using controlled traffic and zero-till, and a 6% increase using controlled traffic and light, shallow tillage, compared to conventional random traffic and full tillage practices (Wang *et al.*, 2009). The changes in profit for the controlled traffic, zero-till system were brought about by 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.

Controlled traffic adoption in the Australian cane industry has increased due to evidence produced by the Sugar Yield Decline Joint Venture (SYJVD) program (1993 – 2006). A combination of controlled traffic, legume break crops and reduced and zonal tillage practices has resulted in significant economic advantages for cane production. Information arising from the SYJVD led to changed farming operations for a number of growers. In one case, major reductions in land preparation and planting operations, resulting in a 54% reduction in tractor use, contributed to improvement in Return on Investment from 1.6% to 2.7% (Carr *et al.*, 2008).

The literature on the economics of controlled traffic conversion is very much focused on the grain and cane industries. Very little has been reported in the vegetable industry, perhaps partly because very little CTF research or adoption has been done in vegetables. Given the current level of incompatibility in vegetable machinery configurations, early adopters in the vegetable industry are likely to move to seasonal CTF. Seasonal CTF is an interim step towards fully integrated CTF in which the incapacity to integrate some machinery, particularly vegetable harvesters, into the CTF system is accepted. All other operations are conducted on permanently located wheel tracks (Vermeulen *et al.*, 2007). Post-harvest tillage is more likely to represent conventional practice. Seasonal CTF is seen as a starting point for the vegetable industry as it can be achieved without excessive investment.

Analysis of a typical vegetable enterprise in the Lockyer Valley (Queensland) suggests that moving to seasonal CTF can provide a return on investment (ROI) of over 26% on the cost of guidance equipment through savings in tractor capital and operating costs, and labour costs (Page, unpub data). Costs of machinery modification were not included in this analysis.

2.2 Greenhouse gas emissions – sources and the impact of controlled traffic

Greenhouse gases (GHGs) produced by economic activity are believed to be a major contributor to climate change. Carbon dioxide is the most important GHG by volume. Horticultural production emits, in various quantities, carbon dioxide from fuel and soil sources, fluorocarbon gases from refrigeration, and nitrous oxide from soil. Some of these gases are emitted in small quantities, but have a significant global warming impact per unit volume. For simplicity, the overall impact is expressed in terms of Carbon Dioxide Equivalent (CO_2-e).

Although the recently proposed carbon tax specifically excludes agriculture, horticulture will inevitably face increased costs when these measures eventually come into play. Present proposals exclude payments for on-farm emissions, but these could well be an issue in future. Incentives for emission reduction are under consideration. Additional costs can be expected from suppliers as a result of the flow on effects of taxes related to manufacture of inputs.

2.2.1 Input-Related Emissions

2.2.1.1 Fuel

The ease of calculation of GHG emissions varies considerably across the range of inputs. Fuel, burned in tractors and field machinery, produces 2.9, 2.3 and 1.5 kg CO_2-e/L for diesel, petrol and LPG respectively. Emissions from this source can be easily calculated from purchase records for an existing operation. When considering the effect of system change, it is necessary to estimate fuel use in both the current and improved systems, so from a modelling perspective, purchase records are only useful for a specific situation that represents current practice.

Changes that reduce both the requirements for tillage, and the energy requirements for any given operation, are obvious ways to reduce emissions. In vegetable production, energy intensive tillage operations are required to undo the compaction damage caused by harvest traffic, and to reduce the resultant clods to a size suitable for a seedbed. Restricting heavy machinery to permanent traffic lanes (i.e. controlled traffic) is an important step to reducing the need for tillage, and the energy required for field operations.

2.2.1.2 Agricultural chemicals

Agricultural chemicals embody varying amounts of energy for their basic materials, manufacture and transport to the farm. On-farm system changes which (for instance) reduce tillage, but increase herbicide use, do not always reduce overall energy requirements and emissions. Energy data for fertilisers and pesticides commonly used in Western Canada has been tabulated (Zentner *et al.*, 2004), and some data is also available in Rab *et. al.* (2008).

System changes to reduce pesticide requirements can be extremely complex, but some aspects, such as targeted application, are straightforward. The percentage of agricultural chemicals that actually achieve their biological function is very small, because most are broadcast uniformly over the paddock, and do not contact the target. The use of "band" application techniques with precision guidance could substantially reduce pesticide use in horticultural row crops. While a fully integrated controlled traffic system is not essential for this approach, the spatial precision and repeatability offered by controlled traffic makes banding an achievable option.

2.2.1.3 Fertilisers

Nitrogen fertiliser manufacture is energy intensive (Woods and Cowie, 2004) and represents a large embodied energy input to cropping. Nitrogen use efficiency can be very poor, with mean values often < 40% (Raun and Johnson, 1999). Nitrogen losses occur from volatilisation, or by leaching or runoff following rainfall or irrigation when soil nitrate levels are high. Denitrification losses can be substantial from soil with high levels of water filled porosity (i.e. approaching waterlogged) (Rochette *et al.*, 2008). Emissions related to phosphorus and potassium are much smaller.

Options to improve fertiliser use efficiency include targeted application to the places and times when the crop requires the nutrient. This can be particularly important for nitrogen, as losses between application and actual plant use can be rapid depending on weather and soil conditions. Accurate spatial and temporal placement depends on the use of precision guidance to target placement of slow release fertiliser relative to the crop, or the ability to access the crop for precise placement when the nitrogen is required. Both approaches are easier and more reliable using permanent, compacted traffic lanes to facilitate field access soon after rainfall or irrigation.

2.2.2 Soil Emissions

Emissions of greenhouse gases from the soil are the result of complex processes, strongly influenced by temperature, moisture content, biological activity, nutrient availability, clay content and physical structure. Despite considerable efforts to model and estimate soil carbon levels and emissions, the poor reliability of estimates, and the cost of direct measurements, are regularly given as reasons to exclude soil sequestration and emissions from GHG market mechanisms. Nevertheless, an effort has been made in this review to provide some background to the issue, and the management changes that might be expected to provide economic and GHG emission benefits.

2.2.2.1 Nitrous oxide

Nitrous oxide has approximately 310 times the greenhouse impact of carbon dioxide, so small quantities have a significant global warming effect. Many authors have demonstrated a relationship between emissions and soil compaction, porosity and pore connectivity. Carbon dioxide, nitrous oxide and methane emissions are often studied together (Ball *et al.*, 1999). All are produced by soil microbiological activity, and appear to be strongly influenced by tillage, compaction and soil moisture status. Methane (CH_4) has approximately 23 times the greenhouse impact of carbon dioxide, but crop production emissions are small compared with those from animal or paddy rice production. Consequently, methane has not been included in this review, nor was it considered in the model.

Nitrous oxide (N_2O) is produced by the activity of denitrifying microorganisms when aeration is limited (i.e. water-filled porosity > 60 - 75%) and both nitrate and organic matter are available. Nitrous oxide emissions are highly variable in space and time, and are often crudely estimated as a simple proportion of fertiliser N. The IPCC default value is 1.25% of applied fertiliser (Dalal *et al.*, 2003), but smaller values have been measured in broadacre farming in Australia. The Australian Climate Office now uses a default value of 0.3% of applied fertiliser for dryland grain cropping (Officer *et al.*, 2008). This lower value is unlikely to be appropriate for irrigated horticultural production, where wet soil environments occur more frequently than in broadacre grain, and soil is subject to more intensive traffic loads, with consequent impacts on soil compaction.

2.2.2.2 Carbon dioxide

Carbon dioxide (CO_2) is produced by the degradation of carbon-rich soil organic matter (SOM). This is a major component of the "upwards" legs of the well-known carbon cycle, taking carbon dioxide back the atmosphere. This loss of carbon is largely balanced by the "downwards" leg of carbon dioxide absorption and distribution by plants. Plant growth absorbs carbon dioxide from the atmosphere, but much of this returns rapidly to the atmosphere with the breakdown of plant biomass. Surface biomass decomposes quite rapidly, but some is moved into the profile by soil biota. The organic matter decomposition processes release nutrients, a process that is accelerated by tillage. A small proportion of this material is converted into less active, longer-lived carbon forms, (humus and "recalcitrant" carbon).

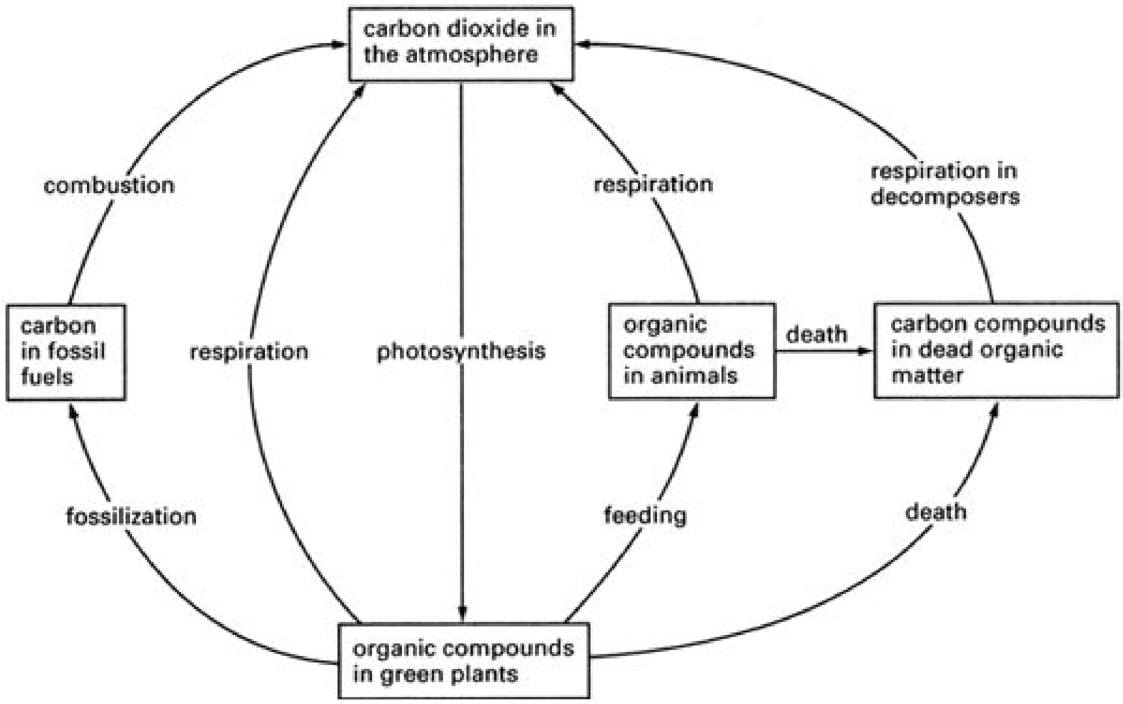


Figure 1. Schematic of the carbon cycle showing the pathways of carbon release to the atmosphere and accumulation in plants.

"Soil carbon" is the net effect or balance between these processes of carbon capture by plants, and carbon loss from soil. Soil carbon levels will generally be greater, for instance, where greater rainfall supports greater biomass production, and/or where lower temperatures reduce the rate of decomposition.

Natural systems achieve a balance over time as vegetation continues to grow and the different components of plant-derived soil organic matter decompose. Soil carbon levels found under nearby natural vegetation are a useful benchmark against which to compare the effectiveness of cropping systems in maintaining soil quality.

Soil carbon, its loss, and potential sequestration, has been reviewed by a number of authors (Sanderman *et al.*, 2009). Loss of soil carbon is an issue from a number of perspectives:

- Carbon contributes to the ability of soil to form stable, erosion-resistant aggregates and hold water in plant available form. Soil carbon is also important to the storage of plant nutrients, so it has considerable economic value to farmers.
- Surface soils (worldwide) contain roughly twice the amount of carbon as the atmosphere. Loss of soil contributes to climate change, and conversely, increasing soil carbon should help mitigate this effect, although there is considerable debate about the actual amount of carbon that can be sequestered through this process.
- Farming operations return less carbon to the soil than natural systems, because most cropping systems are less efficient than natural vegetation at producing biomass – a temporary monoculture (cropping), including periods of crop senescence and fallow – will rarely match a polyculture (most natural systems) for biomass production per hectare. Cropping also removes the "economic" component at harvest, and this is rarely recycled.
- Soil carbon loss is accelerated when soil aggregates are disrupted, increasing the oxidation of SOM. Tillage is the major mechanism of disruption, but some occurs even in minimum-disturbance operations. Field traffic disrupts surface aggregates and accelerates residue breakdown. Furthermore, random traffic almost guarantees the need for more tillage, particularly in intensive vegetable production.

2.2.3 Field management effects on soil emissions

Almost every aspect of soil and crop management influences emissions, but a small number of factors stand out as being of critical importance:

- *tillage* - loosening soil involves burning diesel, and encourages soil carbon loss by breaking up soil aggregates and exposing SOM to oxidation. Conventionally, growers see tillage as necessary to restore soil structure following traffic compaction, manage weeds and bury crop residues.
- *traffic* - driving machinery across soft, cultivated soil wastes energy. Heavy vehicle traffic is probably the single most important reason for poor soil structure in vegetable production. Each field operation imposes heavy wheeled traffic over 20 – 30% of the land area. Exceptions are spraying (~5% tracked area) and harvest, which for some crops, can be close to 100%. Over the course of a growing season, from primary tillage to harvest, 100% or more of most horticultural field surfaces will receive wheel traffic, and some areas will receive 2 - 3 traffic events.
- *fertiliser* - on average, less than 40% of applied N is used by crops (Cassman *et al.*, 2002). Excess soil nitrate is easily lost by runoff, leaching or denitrification. Some is also lost as nitrous oxide, and may be a significant contributor to soil GHG emissions.

Soil structure is easily degraded by repetitive cycles of tillage and compaction when field traffic is not controlled. Heavy wheel loads on soft soil produce surface ruts and subsurface compaction, both of which reduce porosity, pore connectivity and internal drainage. Tillage has long been the only practical solution to this problem, but this has some damaging and far-reaching consequences. Directly, tillage buries residue and accelerates organic matter loss, and indirectly, because horticultural systems have traditionally buried residue, most vegetable seeding equipment is designed to operate in residue-free environments. The outcome is that even when the need for tillage is removed or minimised, such as under controlled traffic, it is not always possible to retain residue because seeding equipment for the subsequent crop is incapable of operating in those conditions.

Controlled traffic is also difficult to achieve because the wheel placement on horticultural harvesting equipment is a matter of design convenience, rather than soil protection. The issues highlighted above make it difficult for the intensive vegetable industry to avoid the soil structural degradation caused by repetitive cycles of traffic and tillage, together with the accelerated degradation of crop residues through tillage.

Tillage accelerates soil carbon loss and related carbon dioxide emissions. Stopping tillage increases the prospect of improving soil carbon, but this has not always been achieved. Other system effects such as climate, rotation and soil condition are also important (Govaerts *et al.*, 2009).

The same is broadly true of nitrous oxide emissions, as reported in a summary of results from 25 reports representing 45 site-years of data (Rochette, 2008). It was concluded that tillage impacts on nitrous oxide emissions were small in soils with good to medium aeration and drainage. However, in poorly-aerated soils, nitrous oxide emissions from no-till systems were greater (and sometimes much greater) than from tilled systems. This was explained by the increased frequency with which water-filled pore space exceeded 60% under no-till conditions in fine-textured, poorly drained soils.

The reports cited above rarely define the precise measurement site in relation to prior wheel traffic. In the absence of specific information, it is reasonable to surmise that researchers would avoid placing emission monitoring devices in obvious wheel tracks (Rochette, pers. comm., 2010), where reduced porosity can be expected even in naturally well-drained soils. Wheel track emissions are not commonly studied, and yet wheel tracks can represent a significant proportion of a paddock in vegetable production systems – and if top-dressed fertilisers are broadcast, rather than accurately placed in the row, a significant proportion of the fertiliser lands in the wheel tracks.

Nitrous oxide emissions from non-wheeled inter-rows, wheeled inter-rows and ridges in a potato paddock were observed in the ratio 1:8:0.17 in European research (Ruser *et al.*, 1998). Similar monitoring of emissions from potato production on a well-drained soil in New Zealand reported nitrous oxide emissions in the ratio 1:6:2.4, from a system with less fertiliser in the inter-rows (Thomas *et al.*, 2004). Both studies concluded that nitrous oxide emissions were driven by high levels of water-filled porosity, both identified tractor wheel compaction as a major factor, and both found quite similar ratios of emissions from non-wheeled and wheeled inter-rows. These results are entirely consistent with the conclusions of earlier Scottish research (Ball *et al.*, 2008), and suggest the importance of accurate fertiliser placement as a strategy for reducing nitrous oxide emissions.

2.2.4 Soil emissions and controlled traffic

Research into the impact of controlled traffic on greenhouse gas emissions is rare. Monitoring of emissions from organic vegetable production in the Netherlands over a two-year period showed that seasonal controlled traffic reduced mean nitrous oxide emissions by 20 – 50% compared to random traffic (Vermeulen and Mosquera, 2009). The methane balance also changed from one of small emissions to small, steady absorption, a result similar to that found by Ruser *et. al.* (1998). These results can be explained by the improved porosity of soil managed with seasonal controlled traffic, which was consistently greater than that of random traffic.

Emissions might also be expected to be greater from the organic production system investigated in these studies, as all fertiliser was applied as animal waste slurry in one operation. Multiple applications, better aligning nitrogen supply with crop demand, should reduce the period during which excess fertiliser is available for denitrification, and thus reduce nitrous oxide production. The timeliness advantages of controlled traffic should assist in this management practice.

The seasonal controlled traffic system referred to above entailed an annual overall plough tillage operation, and severe random wheel compaction effects would still be present beneath ploughing depth. This suggests that permanent controlled traffic could make significant improvements on the 20 – 50% reduction in nitrous oxide emissions measured in seasonal controlled traffic by Vermeulen and Mosquera (2009).

Consideration of the literature led Tullberg (2010) to conclude that controlled traffic would produce a very substantial reduction in greenhouse gas emissions from all sources, including a reduction in soil emissions estimated at 50%. A subsequent pilot trial (Tullberg *et al.*, 2011) indicated that nitrous oxide soil emissions from a controlled traffic paddock would be approximately 40% of those from a random traffic paddock. These tests were carried out in a dryland grain environment, and comparisons with horticulture should be made with caution.

Since soil management impacts on porosity and waterlogging are a major determinant of soil GHG emissions, controlled traffic provides an attractive means of reducing emissions. There are obvious challenges in achieving working, track and tyre width compatibility of all machinery used across a cropping program, but the potential economic and environmental rewards are likely to be substantial.

2.3 Greenhouse gas models

Most carbon models are developed to account for Scope 1, 2 and 3 emissions, as per the definitions adopted by the Intergovernmental Panel on Climate Change (IPCC) [1], viz.:

Scope 1: All direct GHG emissions.

Scope 2: Indirect GHG emissions from consumption of purchased electricity, heat or steam.

Scope 3: Other indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities not covered in Scope 2, outsourced activities, waste disposal, etc.

This is a useful approach if undertaking carbon accounting for an entire enterprise. However, if the purpose is to model and estimate the carbon footprint of a specific element, such as alternative field production systems, it is necessary to consider those factors which either directly influence, or are directly influenced by, the system being changed.

Carbon models for cropping industries must account for fossil fuel energy inputs and CO_2-e emissions embodied in inputs such as fertilizer and crop chemicals. Enterprise-focused models for horticulture must also consider emissions generated by on-farm use of electrical power (e.g. irrigation, post-harvest processing) and leakage of refrigerants etc. Most of these are included in industry-specific carbon calculators. Examples include the recently released Australian Vegetable Industry Carbon Footprint Tool [2] and

HortCarbonInfo [3]. A relatively similar approach is used in the Farming Enterprise Greenhouse Gas Emissions Calculator [4].

These empirical models are calculators which sum the emissions directly related to cropping inputs, such as fuel, pesticides and fertilisers. Soil emissions are included (at best) by use of a crude relationship between nitrogen fertiliser application rate and nitrous oxide emissions. They are not particularly helpful when attempting *a priori* estimates of the emission effects of cropping system change, which might be expected to reduce both the need for energy-intensive field operations, and the magnitude of fertiliser-related soil emissions.

Carbon process models are usually much more complex systems to provide estimates of net soil carbon effects of crop and animal management. Well-known examples in Australia include APSIM [5], Roth C [6] and Full CAM [7]. These are generally sophisticated models developed over many years to simulate biochemical processes, predict carbon and nitrogen balance and emissions of carbon dioxide, nitrous oxide and methane. Inputs to these models include data on climate, soil, vegetation, and farm management inputs, to allow assessment and balance for a large number of process parameters and intermediate and final products. These models are based on fundamental science, adjusted and validated against long-term trial data. The difficulty in applying them is that of establishing management system effects on a large number of soil parameters, on a layer-by-layer, time series basis, or the alternative difficulty of imprecise accounting for soil management effects by broad, categorizations (e.g. "conventional", "reduced" tillage, "single cropping", "stubble grazed" etc.). These models are robust enough to accommodate different crop types, but most validation work has been done with grain crops, and there is little reliable input data for vegetable cropping scenarios in Australia. They rarely take account of inputs-related emissions (fuel, agrichemicals).

A small number of intermediate models combine simplified versions of the process models (usually mean outcomes within specified soils, geographical areas and farming systems) with the inputs summaries of the empirical models. Most have been developed in anticipation of a soil carbon trading system, such as that now in operation in Alberta, Canada. This system is based on Agriculture Canada's Holos [8] in which user data requirements are greatly simplified by map-accessed climate and soil data. Industry restrictions allow the use of empirical rules validated within that industry, and soil management processes are closely defined. A local example including a much greater degree of empiricism is the Farming Enterprise Greenhouse Gas Emissions Calculator [4], based on the SOCRATES model (Grace *et al.*, 2006).

Process models are generally too complex for non-specialist use, whilst empirical and intermediate models are usually available on-line to farmers and their advisers. Most suggest farmer use as a basis for system change to reduce carbon footprint, and attempt to identify some major sources of emissions.

Empirical and intermediate models are usually less useful in indicating the steps which might reduce emissions, because they do not drill down into the detail. The most obvious example is fuel. Empirical models consider only total use, without regard to the engines and operations consuming that fuel. The more highly developed intermediate models, such as Holos, include more detailed definitions of crop production systems, particularly the extent of change to reduced or zero tillage, and the

Alberta Soil Carbon Protocol [9] includes tight specifications of all soil engaging equipment and operations.

This project is concerned with controlled traffic in the vegetable industry, a scenario which is quite different from those addressed by most existing models. Controlled traffic avoids the repetitive soil compaction and re-loosening operations that are a common feature of vegetable production. This will reduce the number, degree of disturbance and energy use of tillage operations. A reduction in wheeling and tillage will improve soil structure and biological activity, with likely positive effects on soil organic matter levels and the carbon balance.

System effects of controlled traffic (timeliness & trafficability) may also allow greater cropping frequency and greater biomass production. Improved permeability will reduce the frequency and duration of waterlogging, and should therefore improve nitrogen fertiliser use efficiency and reduce nitrous oxide emissions. This is important when nitrogen fertilizer often represents the greatest single energy (i.e. carbon) input to crop production, and its inefficient use produces the major source of soil emissions – nitrous oxide.

3. Materials and Methods

3.1 Economic model development

3.1.1 Background

The economic comparison between the conventional, seasonal controlled traffic and controlled traffic systems is by an analysis of gross margins, and a comparison of changes in machinery costs and return on investment in plant and machinery.

A gross margin is defined as the gross income from an enterprise less the variable costs incurred in producing it. Variable costs are those costs directly attributable to an enterprise and which 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 roughly 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 gross margins generated by the model are quoted per cropped hectare across the full rotation.

The calculation of a gross margin is the first step in farm budgeting and planning. It enables a direct comparison of the relative profitability of enterprises that compete for similar resources, and consequently provides a starting point for determining the overall enterprise mix on the farm. It should be noted that where different enterprises require different resources, such as machinery, labour and capital, additional calculations should be undertaken to determine if the change to the enterprise mix is worthwhile.

The gross margin model developed in this project is based in Microsoft Excel®. The basic structure of the model was drawn from existing economic models used for the Tasmanian vegetable industry. The model allows selection of different inputs and crop rotations for different management systems. The model uses crop choices, rotations and economics relevant to the Tasmanian vegetable industry, and relies on information from a range of sources, including some collected as part of past and current projects conducted in the Tasmanian vegetable industry. All inputs to the model, such as costs of equipment, fertiliser, fuel, power etc. were current as of June 2011. The model calculates the gross margin for individual crops and the average gross margin for all crops across the selected rotations. It also calculates the equipment overhead costs based on the capital value and current rates of interest and depreciation.

Models to accommodate a number of farm scenarios were developed to represent vegetable farming enterprises in the Tasmanian industry, ranging from intensive vegetable-only operations in the north-west of the State, to mixed vegetable/livestock enterprises in the northern midlands region.

3.1.2 Input variables

Input values for the models can be changed to reflect the requirements and performance of the three different cropping systems considered – conventional, seasonal CTF and fully integrated CTF. The variables include:

- % yield variation
- % change in fuel use for tractors
- % change in operating time for tractors
- % change in irrigation water use

- % change in fertiliser use
- The number and prices of major pieces of equipment required, such as tractors, guidance technology, tillage implements etc.

Variables such as tractor fuel consumption (L/h), work rates (ha/h), hours per year of work, interest rates, depreciation rate and insurance are also adjustable, but these were not altered as part of the scenario testing that is reported in the Results section.

3.1.3 Baseline assumptions

Assumptions regarding equipment and crop inputs have been provided as a guide for use of the model, and are summarised in Table 1. The tractor and equipment details in Table 1 are applicable for a large vegetable farming operation (270 ha) on the north-west coast of Tasmania, which was the base model developed for this project. Smaller operations would have different equipment requirements.

Table 1. Baseline assumptions (changes compared to conventional production system) for economic models

SCTF	CTF
Yield	
Up to 10% increase	Up to 20% increase
Tractor requirements	
One large tractor required (*cf*. two for conventional system)	No large tractor required
Up to 10% reduction in fuel use and operating time, for large tractor	
Up to 10% reduction in fuel use and operating time, for medium tractor	Up to 30% reduction in fuel use and operating time, for medium tractor
No change in fuel use or operating time for light tractor	No change in fuel use or operating time for light tractor
Guidance equipment required for some tractors	Guidance required for all tractors
Equipment	
One mouldboard plough (*cf*. two for conventional system)	No mouldboard plough
One modified deep ripper (*cf*. two standard for conventional system)	One modified deep ripper
One modified rotary hoe (*cf*. two standard for conventional system)	One modified rotary hoe
Irrigation	
No change in application method, maximum 10% reduction in water use	No change in application method, maximum 10% reduction in water use
Fertiliser	
No change in application method, maximum 10% reduction in fertiliser use	No change in application method, maximum 20% reduction in fertiliser use

The model allows rotations to be constructed from a selection of crop options covering the major crops grown in the Tasmanian vegetable industry, including green manure and fallow phases. The duration of each crop phase is entered as part of the rotation design. Rotations can be kept the same for the different management systems to determine the influence of yield increases and input reductions on gross margins, independent of any change to the crop selection. Alternatively, different rotations can be selected for conventional and CTF options. This makes it possible to reflect system benefits that may possible with CTF, but which would not be recommended practice under conventional cropping situations. For example, in some situations, new crops can be planted immediately following harvest under CTF, whereas time for tillage would be required under conventional practice. This may provide scope for an opportunity crop, or earlier planting of a crop, which is not possible in the conventional system.

3.1.4 Machinery operating costs

The model uses estimates of operating costs for tractors and plant based on a categorisation of heavy, medium and light work. Factors relevant to the calculation of operating cost are:

- diesel consumption of 25, 15 and 8 l/h for heavy, medium and light work, respectively
- work rates of 0.5, 0.7 and 2.0 ha/h for heavy, medium and light work, respectively
- diesel = $1.35/L net
- oil = 2.5% of diesel use at $4.50/L
- Repairs and Maintenance (R&M) = 2% of purchase price

3.1.5 Contractor costs

Contractor costs have been included in the gross margins where appropriate - e.g. sowing, fertiliser cartage and harvesting and cartage of crops.

3.1.6 Farm overheads

Direct labour costs have been included in the gross margins. These are based on current rates in the Tasmanian Horticultural Award. Labour rates include 9% superannuation and 4.5% workers compensation.

It has been assumed that there will be no change in general overhead costs - e.g. rates, communications, accounting etc. Changes in machinery insurance costs would be expected on the basis of changes capital costs, and these have been included in the analysis.

3.2 GHG emissions model development

The GHG component of the model developed includes emissions from fuel used for tillage, pesticide contributions, and some estimates of nitrous oxide emissions. Modelling of GHG emissions is a complex process, particularly in relation to soil emissions. The treatment of soil emissions in this model is inevitably a gross simplification, as the models required to do this topic justice are very complicated, and data relevant to vegetable production systems is extremely limited.

The GHG emissions component of the model is a modified version of a Microsoft Excel® based model originally developed to investigate the impact of CTF adoption on GHG emissions in the dryland grain industry (Tullberg, 2010). It is not a comprehensive model that includes all the factors involved in estimating total GHG emissions at the farm level. It incorporates the key elements of GHG emissions associated with those aspects of vegetable production operations which are anticipated to change with different traffic and tillage management systems. This includes pre-farm emissions associated with the supply of fuel, pesticides and fertilizer. On-farm post-harvest emissions are excluded.

In the context of this model, emissions can be broadly divided into inputs (fuel, fertiliser and pesticides) and soil emissions (fertilizers, organic matter degradation). Estimated reductions in GHGs from inputs are the result of improved input efficiency. Input-related emissions are generally easily quantified for a specific enterprise (at least in principle). On the other hand, soil emissions are much more variable, and more difficult to measure or predict, although they can be large.

3.2.1 GHG related inputs included in the model

Emissions were calculated in the categories of "on-farm" and "manufacture". This allowed the impact of changes in inputs (such as fuel and fertilizer) to be calculated at both the farm level and the life-cycle level. Fuel, fertiliser and pesticides each have GHG emissions associated with their manufacture and supply. They also have on-farm GHG emissions associated with their use, such as burning diesel in tractors. There are also on-farm emissions associated with the use of nitrogenous fertilizers in particular soil conditions. In summary, the model deals with emissions in the following categories:

1. Fuel use in tractors – on-farm and manufacture/supply
2. Fertiliser – manufacture/supply only. Fuel use for fertiliser application is covered in point 1, and fertiliser related soil emissions are covered in point 4.
3. Pesticides – manufacture/supply only. Fuel use for pesticide application is covered in point 1
4. Fertiliser related soil emissions – on-farm only

These categories are not in strict alignment with the Inter-governmental Panel on Climate Change (IPPC) accepted definitions of Scope 1, 2 and 3 emissions, defined as follows [1]:

- Scope 1: All direct GHG emissions.
- Scope 2: Indirect GHG emissions from consumption of purchased electricity, heat or steam.
- Scope 3: Other indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities not covered in Scope 2, outsourced activities, waste disposal, etc.

The reason for this is quite deliberate in the context of this project. The objective was to determine the economic and GHG emissions impacts of changing vegetable production systems, with particular reference to tillage and traffic management. The IPCC definitions would require all emissions generated on the farm to be accounted for under Scope 1 emissions. This project was only concerned with the emissions changes that occur as a result of changing production systems (i.e. up to and including harvest). Likewise, if a management change improves N fertilizer efficiency, for example, the beneficial effects extend beyond the nitrous oxide production on the farm, and include changes to the emissions associated with fertiliser manufacture and transport. It is the emissions of the farming system and its inputs that are of interest in this case, not the identification of which operator in the system is responsible for the emissions.

3.2.2 Calculating emissions for each input

The GHG component of the model is linked directly to the same values that are used in the economics component. Therefore, adjusting various input factors as outlined in Section 3.1.2 also adjusts the results for GHG emissions. All GHG emissions are calculated in terms of kg CO_2-e (carbon dioxide equivalents), which accounts for nitrous oxide having a warming potential which is 310 times that of carbon dioxide.

The priority has been to work with data which might reasonably be obtainable from growers, and provide information which will be useful to growers and policymakers considering the economic and emissions impacts of changing traffic and tillage systems. The model should provide a reasonable indication of the relative magnitude of emission changes resulting from practice change, and the relationship between soil emissions and those related to inputs. The authors make no claims to absolute precision.

3.2.2.1 Fuel

Industry accepted multipliers are available to calculate GHG emissions for both the on-farm use and the pre-farm supply components of diesel fuel used in tractors. The factors used are 2.67 kg CO_2-e/L for on-farm use and 2.89 CO_2-e/L for pre-farm manufacture and supply [10]. Changes in fuel use between management systems can be reasonably predicted, and therefore, the estimates of fuel related GHG emissions are likely to be quite precise, within the bounds of the estimated changes to fuel use.

3.2.2.2 Pesticides

Estimates of emissions for the pre-farm component of pesticide use are available from a number of sources. The most comprehensive source is Canadian, but does not cover all chemicals commonly used in Australian horticulture. GHG related information on specific pesticides is very difficult to access. An approach used by Unilever provides one single mean emission value per treatment. The factor used in this model was 20.5 kg CO_2-e/ha/application [11]. The accurately known factors which influence calculation of the pre-farm pesticide related emissions are the application rate and the number of applications made for particular crops. It is possible that adoption of alternative soil management strategies could influence pesticide use – e.g. a transition to zero-till requiring use of more herbicides. No provision has been made for this possibility in the model, as the future trends in that area are difficult to predict.

3.2.2.3 Fertiliser

Estimates are available from a number of sources and studies for the pre-farm component of fertiliser manufacture and supply. Estimates vary depending on the method of production. The factor used in this model was 3.25 kg CO_2-e/kg elemental N (Rab *et al.*, 2008). The accurately known factors which influence calculation of the pre-farm fertiliser related emissions are the % elemental N in the fertiliser used, and the application rate for particular crops. What is not well known at this stage is the likely (or possible) reduction in fertiliser use which may arise through the adoption of controlled traffic. The on-farm soil emissions related to fertiliser are discussed in the following section.

3.2.2.4 Soil emissions

The factors of most interest in relation to soil GHG emissions are nitrous oxides from the denitrification of nitrogen from fertilizers, CO_2 from the decomposition of organic matter, and, on the benefit side, sequestration of carbon through the retention of organic matter. The science related to all of these areas is complex and far from settled.

3.2.2.4.1 Carbon dioxide

Carbon dioxide (CO_2) is produced continuously by oxidation of soil organic matter, but vegetated systems (natural or managed) continuously absorb CO_2, varying amounts of which are returned to the soil in plant residues. CO_2 emissions, organic C return in residues, and residue breakdown in the soil are system dependent, but their net impact is expressed in soil carbon level.

It is recognized there is tremendous capacity to sequester carbon in soil through changes in management practices, particularly the changes that are possible with CTF (Tullberg, 2010). There is little doubt that intensive tillage-based crop production has diminished soil carbon levels (Cotching, 2009) while reduced or no-tillage systems can reduce or even reverse the process of carbon loss (Havlin *et al.*, 1990). A review of the literature found the science surrounding the issues of soil emissions arising from tillage, and sequestration due to residue retention, is ambiguous and not sufficiently refined to incorporate in a simple model of this nature.

In general terms, it is recognized that retention of crop residues will sequester carbon in the short term, and tillage releases carbon dioxide through oxidation processes. On that basis, it can be assumed that the opportunity to reduce tillage under CTF is a positive in GHG emission terms, but there is insufficient data to include this in a meaningful way in a simple model.

3.2.2.4.2 Nitrous oxides

Nitrous oxides have 310 times the warming potential of carbon dioxide. They are of interest from a farming system perspective, as changes in soil structure recorded under controlled traffic have the potential to significantly reduce denitrification in cropping situations. They are also of economic interest, as emissions of nitrous oxide represent loss of fertilizer applied by the grower.

Soil conditions of high water filled pore space are conducive to denitrification, and research has shown that these conditions more likely to occur under conventional traffic and tillage systems than under controlled traffic (Dalal *et al.*, 2003). Table 2 summarises the role that controlled traffic may have in reducing nitrous oxide emissions.

To some extent, some of the detail in Table 2 is speculative, but Canadian research has pointed to the broad evidence that soil conditions exhibiting high water filled pore space generate significantly more nitrous oxides that those which are porous and well drained (Rochette *et al.*, 2008). This effect, and it's likely magnitude, has been demonstrated in Australia in pilot trials (Tullberg *et al.*, 2011). The component of the model which attempts to predict nitrous oxide emissions is largely based on this knowledge. It is acknowledged there is a lack of knowledge regarding the duration of conditions conducive to nitrous oxide generation under Tasmanian conditions. However, data from other projects (specifically MT09040 - Development and demonstration of controlled traffic farming techniques for production of potatoes and other vegetables) suggest that controlled traffic provides soil structural conditions which minimise the high water filled pore space conditions that favour nitrous oxide generation.

Table 2. Comparison of impacts of conventional and controlled traffic farming systems on nitrous oxide generation

Conventional	Controlled traffic	Effect on NOx
Lower porosity and higher water filled pore space in wet conditions.	Higher porosity with greater aeration and lower water filled pore space.	Nitrous oxide generation increases rapidly at high water filled pore space, so is less likely to occur under controlled traffic.
Poorer internal drainage, so soil stays wet (high water filled pore space) for longer.	Improved internal drainage, so returns to lower water filled pore space conditions sooner after saturation.	The time available for denitrification to occur is reduced under controlled traffic.
Trafficability conditions may dictate when fertilizer is applied, rather than it being applied precisely when required by the crop. Lack of precision may dictate that fertilizer is broadcast, rather than placed close to the plant and the site of use, with some fertilizer landing in wheel tracks leading to high losses.	Improved trafficability under controlled traffic provides a wider time window for application of fertilizer, with the potential to apply more precisely both temporally and spatially.	More precise application of fertilizer, both temporally and spatially, should result in more efficient use of the fertilizer by plants, with both less fertilizer and less time available for denitrification processes.

The accurately known input to the model is how much nitrogen is applied to each crop. The model estimates nitrous oxide production on the basis of the amount of elemental nitrogen applied, combined with details of the season of application, and the likelihood that periods of high water filled pore space will occur while unused nitrogen fertiliser is available in the soil. For example, it is logical that a pre-season application of nitrogen to wet soil in winter is more likely to generate nitrous oxides than an in-season application to a growing crop in summer.

The model attempts to identify the key factors that influence nitrous oxide emissions, and applies some assumptions based on local knowledge. The factors considered are:

- Mean % NOX/applied N – estimates of this factor vary, and the factor used in the model is the IPCC factor of 1.25% (Dalal *et al.*, 2003)
- % area of wheel track/non-wheel track under different traffic management systems – as the previous factor is derived from conventional production systems, and it is known that soil conditions vary significantly between systems, this ratio will influence the total emissions. Wheel track area under controlled traffic vegetables is generally 25 – 30%, while under conventional systems, it can be 100%. Although tillage is used extensively to remediate compaction, as far as soil conditions which influence nitrous oxide emissions, this will only be effective to the depth of final seedbed preparation operations.

- The influence of broadcast versus drilled emissions – this relates to the perceived benefit of spatially accurate placement of fertilizer, and the avoidance of placing fertilizer in the wheel tracks, as occurs when broadcast.
- The number of days for which the supply of nitrogen is in excess of crop requirements – this relates to the difference between pre-sowing application and in-crop application. The model uses estimates based on local practice and knowledge of conventional farming systems.
- The proportion of days with high water filled pore space during the period of excess nitrogen. The model uses estimates derived from local rainfall records and assumptions about the condition of the soil based on recent observations and measurements in other controlled traffic research projects (e.g. MT09040 - Development and demonstration of controlled traffic farming techniques for production of potatoes and other vegetables).

Estimation of system change impacts on nitrous oxide emissions must take account of:

- Emissions factor, E = 1.25% as defined above
- Rate of nitrogen application, N_r = kg elemental N/ha
- Timing of nitrogen application, resulting in D days when excess N is available.
- Placement of nitrogen, being drilled or banded on crop beds when using controlled traffic, or broadcast under conventional systems, with the assumption that emissions are reduced by 10% if accurately placed.
- Rainfall probability after N application, expressed as R% rain days, with W% of those rain days producing near- waterlogging conditions.
- Emission time, $T = D \times R \times W_{ctf}$ or $_{conv}$
- Wheeled area in controlled traffic, A_{wctf} = traffic lane width/(bed + traffic lane width).
- Non-wheeled area in controlled traffic, $A_{nwctf} = (1 - A_{wctf})$
- Wheeled area in conventional (random) traffic, A_{wconv} = grower estimate, generally close to 100% for vegetable production systems
- Non-wheeled area in conventional (random) traffic, $A_{nwconv} = (1 - A_{wconv})$

where subscripts $_{ctf}$ and $_{conv}$ indicate controlled and conventional traffic systems, $_{w}$ and $_{nw}$ indicate wheeled and non-wheeled areas of the soil.

Therefore, emission estimate for controlled traffic

$$= 470 \times E \times N_r \times [(A_{nwctf} \times T_{nwctf}) + (A_{wctf} \times T_{wctf})]$$

where 470 is the conversion factor to kg/ha CO_2-e

The estimates of nitrous oxide emissions generated by this model must not be taken as definitive. This area of science is complex and has a tendency to produce highly variable results. The aim in this project was to use reasonable estimates of some of the key factors that influence nitrous oxide emissions to indicate the relative importance of this greenhouse gas in the overall context of on-farm emissions as farming systems change from conventional to SCTF and CTF.

3.3 Modelling of various scenarios

3.3.1 Variables used

Although data from CTF experiences in vegetables are very limited, a number of assumptions regarding the benefits of CTF can be made with a reasonable degree of confidence. For example, concurrent work investigating CTF in vegetables (MT09040 - Development and demonstration of controlled traffic farming techniques for production of potatoes and other vegetables) has demonstrated reductions in the number of tillage operations required for seedbed preparation, and estimates of fuel use reductions of up to 80%, although 50% is likely to be a more common occurrence. Experiences in a wide range of industries suggest yield increases in the range of 10 - 20% under CTF. Data from seasonal CTF is limited to a few isolated examples from Europe, but there are suggestions of yield improvements of similar order by Vermeulen *et.al.* (2007).

While both research and commercial experience with CTF in vegetables is limited, it is necessary to use best estimates for factors such as yield increase, fuel and time reductions, changes to water and fertiliser use, and the costs and savings associated with modifications to, and reductions in, the equipment fleet. Details are given in Table 3.

The model allows for changes to be made to the number and prices of major pieces of equipment used on the farm. While this allows capital cost to be adjusted depending on the chosen equipment suite, it does not lend itself to simple comparison of the influence of capital equipment cost, and associated overheads, on the gross margin. For many pieces of equipment, an accurate cost is not known for conversion to controlled traffic compatibility. In addition, there is a wide disparity between farms regarding the level of investment in tractors and equipment required for vegetable production, and this inevitably leads to questions as to the accuracy or relevance of a generic model. A simple variation was introduced to allow adjustment to the capital cost by set percentages compared to the cost of the "standard" equipment suite. This allowed the capital cost of equipment to be compared to other variables in the context of its influence on the economic outcomes predicted by the model, which provides an indicator of both the importance (or otherwise) of accurately estimating the costs of equipment modification and of the overall equipment suite. Details of the ranges used for this variable in scenario modelling are given in Table 3.

There is some concern amongst growers that the adoption of controlled traffic will lead to increased harvest costs, specifically for crops such as carrots, onions and potatoes. This is based on two issues:

- Capital or modification cost of alternative technologies to accommodate the need for track width integration and different materials handling scenarios.
- Reductions in field efficiency because of the need for harvesters to travel to the end of the paddock to unload. Random travel across the paddock to access trucks, or trucks driving onto the paddock, are not appropriate vehicle management strategies for controlled traffic.

Assessing the first of these issues in the model can be accommodated through varying the capital cost of the equipment suite, or individual pieces of equipment, as outlined above.

The second issue is accommodated in the model by the provision of a variable to allow the harvest costs of root vegetables to be adjusted by a nominated percentage increase over the current cost. Details of the ranges used for this variable in scenario modelling are given in Table 3.

Table 3. Ranges of key inputs and outputs used to compare conventional, SCTF and CTF vegetable production systems

	Range of change used in model compared to conventional practice	
Factor	**SCTF**	**CTF**
Fuel use [A]	0 – 10% reduction	0 – 30% reduction
Tractor time [B]	0 – 10% reduction	0 – 20% reduction
Irrigation water use [C]	0 – 10% reduction	0 – 10% reduction
Fertiliser use [D]	0 – 10% reduction	0 – 20% reduction
Crop yield [E]	0 – 10% increase	0 – 20% increase
Costs of equipment modification [F]	10% increase	10% increase
Influence of equipment capital cost	0 – 30% increase	0 – 30% increase
Influence of root crop harvest cost	0 – 30% increase	0 – 30% increase

[A] – based on measurement and observation from other projects in Tasmanian vegetable industry
[B] – anecdotal vegetable industry experience broadly consistent with grain industry experience, and relates to reduced operating times of tractors due to reduced tillage requirements
[C] – preliminary vegetable industry data
[D] – consistent with grain industry experience observed in Australia and UK
[E] – Consistent with wide experience over many crops and parts of the world
[F] – based on anecdotal information from other industries

Results were generated by adjusting the variables outlined in Table 3 one at a time. This made it possible to isolate the influence of each factor to determine its relative importance in the overall economic performance of the farming system. The purpose of this was to identify the factors that are most important to capturing the benefits of controlled traffic. In addition, scenarios were tested in which all variables were set at what is conservatively believed to be an "achievable" level (Table 4) to provide an indication of a reasonably expected economic outcome from the adoption of controlled traffic.

Table 4. "Achievable" values of key economic factors used to compare conventional, SCTF and CTF vegetable production systems

	"Achievable" levels of change used in model compared to conventional practice	
	SCTF	**CTF**
Factor	**Range used in model**	**Range used in model**
Fuel use	10% reduction	20% reduction
Tractor time	10% reduction	20% reduction
Irrigation water use	0% reduction	0% reduction
Fertiliser use	0% reduction	0% reduction
Crop yield	5% increase	10% increase
Root crop harvest cost	0% increase	10% increase

3.3.2 Rotation selection

The model allows selection of a range of crops to construct a rotation of up to 25 crop sequences, including periods of fallow or green manure crops. Different rotations were used to generate results for alternative scenarios and different locations. Table 5 illustrates the rotation options used for the north-west farm. One scenario was modelled in which the rotation was kept the same across all management systems. In another, a rotation tailored to capitalise on the timeliness and soil benefits of controlled traffic was used for the CTF system, while the original rotation was kept in place for the conventional and seasonal CTF systems. Both rotations ran for almost 6 years.

Table 5. Rotations used for scenario testing of the model for a north-west vegetable farm.

Conventional and SCTF rotation	Controlled traffic rotation
Potatoes	Potatoes
Wheat	Short term ryegrass (green manure)
Fallow	Onions (spring sown)
Onions (autumn sown)	Broccoli (spring harvest)
Fallow	Beans
Broccoli (spring harvest)	Short term ryegrass (green manure)
Beans	Carrots
Short term ryegrass (green manure)	Short term ryegrass (green manure)
Carrots	Poppies
Fallow	Short term ryegrass (green manure)
Poppies	Potatoes
Short term ryegrass (manure)	Short term ryegrass (green manure)

Alternative rotations were also selected to represent options for the midlands farm, with the same logic applied in relation to a rotation developed to take advantage of some of the soil and timeliness benefits of CTF. The rotations used in the midlands modelling are shown in Table 6. Both rotations ran for 7 years.

Table 6. Rotations used for scenario testing of the model for a midlands mixed farm including vegetables.

Beans	Beans
Fallow	Fallow
Poppies (autumn sown)	Poppies (autumn sown)
Short term ryegrass (green manure)	Short term ryegrass (green manure)
Onions (spring sown)	Onions (spring sown)
Short term ryegrass (grazing)	Short term ryegrass (grazing)
Peas	Peas
Wheat	Wheat
Regrowth after cereal (green manure)	Regrowth after cereal (green manure)
Potatoes	Potatoes
Permanent Pasture	Short term ryegrass (green manure)
	Broccoli (autumn harvest)
	Short term ryegrass (green manure)

As indicated earlier, the controlled traffic rotations are more intense in their production of higher value crops. In the north-west coast model, this is evidenced by not relying on a cereal crop for soil remediation, hence providing the time for an additional potato crop within the same rotational time span. In the case of the midlands farm model, the perceived advantage of controlled traffic is to allow a quicker return to cash cropping after potatoes, allowing production of a broccoli crop instead of relying on a long term pasture phase to remediate soil damaged through potato harvest.

It is clear that the potential for extra high value crops under the controlled traffic system will have a significant impact on the economics of the farming operation. The degree to which the controlled traffic advantages can contribute to higher value rotations is somewhat speculative in the vegetable industry. However, there is ample commercial evidence from other industries (e.g. grain and some leafy vegetables) which support the prospect of more intense production based on the premise that tillage operations or pasture phases are no longer required for soil structural remediation under controlled traffic. This is not to suggest that green manure phases are not required, but perhaps they can be shorter and more frequent under controlled traffic.

Intensifying the rotation is possibly one of the most important economic advantages of controlled traffic, but the impact of that benefit cannot be determined by gross margin analysis at the individual crop level. It is necessary to analyse the performance of the whole rotation in order to determine the influence of those extra cropping opportunities.

3.3.3 Outputs

The outputs of the model are collated in one table. The economic outputs are:

- Average gross margin per cropped hectare across the full rotation.
- Return on Plant & Machinery Investment

Other economic results that can be extracted from the model are:

- Changes in machinery investment, as a % of the conventional system
- Changes in annual overhead costs, as a % of the conventional system
- A graph of Gross Margin for each crop in each management system

The GHG emissions outputs are all expressed in kg CO_2-e per cropped hectare across the full rotation. The GHG outputs are:

- Average farm GHG emissions
- Average soil GHG emissions
- Average fuel GHG emissions
- Average manufacturing GHG emissions
- Average farm and manufacturing GHG emissions

The outputs generated through variation of the input values are presented in the Results section.

4. Results

A detailed overview of the scenario results for a large intensive vegetable farm on the north-west coast of Tasmania is given in the following sections. Results from the modelling of a midlands farm are presented in Appendix A.

A number of graphs are used in this section to present results of the modelling. Unless otherwise noted, the black lines or bars relate to the CTF scenarios and grey lines or bars to Seasonal CTF. All results are shown as a percentage change compared to the conventional system, so the conventional system is not represented in any of the graphs. The x-axis in the line graphs varies depending on the variable, as it has been set at the upper limit of the variable in question.

4.1 Economic measures

Two key indices have been used to illustrate the differences in economic performance of the three management systems. These are:

- Gross Margin – income less variable costs of production for each crop. Gross Margin is a regularly used measure for assessing the contribution of various crops to the overall farm enterprise. The limitation of Gross Margin analysis on an individual crop basis is that it does not account for changes in the capital cost structure, or the cumulative benefit of extra revenue from opportunity or additional crops. This has been addressed in this model by calculating the average Gross Margin over the rotation, in addition to the individual crop Gross Margins.

- Return on Plant and Machinery Investment (RPMI) – total farm Gross Margin less depreciation and insurance as a percentage of total investment in plant and machinery. When assessing the economic performance of a farming enterprise, it would be normal to include all capital costs (including land value) and overheads (including rates and other fixed overheads) in order calculate the Return on Investment. In this model, the capital investment of prime interest is that related to plant and machinery which may change as a result of the adoption of alternative management systems. For example, adoption of controlled traffic generally leads to reduced investment in tractor power, but it won't change the capital cost of the land or the rates. For these reasons, the Return on Investment focuses purely on the investment in plant and machinery – i.e. tractors, implements and irrigation technology.

4.2 Changes to equipment investment

Equipment investment will change with the adoption of either SCTF or CTF. The main changes for SCTF include the purchase of guidance technology, and the integration of tractors and implements to achieve a common track width and a compatible implement working width. Machinery changes for SCTF do not extend to harvest equipment.

For CTF, there is also the need for guidance and compatible track and working widths. Further investment is required to ensure that harvest equipment is also integrated into the system. It is very difficult to estimate the cost of some of those changes, as there is no prior experience with the modification of some of the specialised harvest machinery used in the vegetable industry. Many of the costs associated with harvest equipment will fall to contractors, given the extensive use of harvesting contractors in the Tasmanian industry.

For the purposes of this modelling, the changes in equipment investment are assessed at the farm level, and include changes to tractor inventory, and modification of implements for SCTF and CTF compatibility. The lower draft requirements of CTF generally allow a reduction in the size of tractors required for CTF. The price of conventionally suited tillage implements was increased by 10% to allow for modification to achieve compatibility for SCTF and CTF.

4.3 Farm model

The large farm model for the north-west coast was structured for a cropped area of 270 ha, and an equipment suite to suit.

4.3.1 Equipment investment

With the factors outlined above (Section 4.2) in mind, the capital cost of all plant and machinery chosen to represent the equipment suite of the modelled large north-west coast farm reduced by 5% for SCTF and 15% for CTF. This assessment includes costs allocated to irrigation infrastructure. If considering only the tractor and implement part of the plant and machinery suite, the reductions in capital are 11% and 35% for SCTF and CTF, respectively.

4.3.2 Economic analysis

4.3.2.1 Impact of individual parameters, same rotation

A common rotation (left hand column of Table 5) was used for all management systems, and the variables (Table 3) were changed individually to determine their impact on the average Gross Margin per hectare over the full rotation. The response of Gross Margin to changes in the chosen variables is shown in the graphs (a – e) in Figure 2. Each is shown individually for the sake of clarity. It is assumed there is no increase in root crop harvest costs under SCTF, as there are no traffic management constraints in that system.

It is immediately noticeable from Figure 2 that there is a Gross Margin advantage for both SCTF and CTF, although small in the case of SCTF, even without any change in the chosen variables. This arises because changes in tractor inventory due to reduced tillage requirements automatically reduce fuel use, and therefore have a positive impact on Gross Margin. Increased harvest cost for root crops is one of the few added costs that could detract from the Gross Margin benefits of CTF. Those costs would have to increase by 32% to completely negate the inherent Gross Margin benefit of CTF.

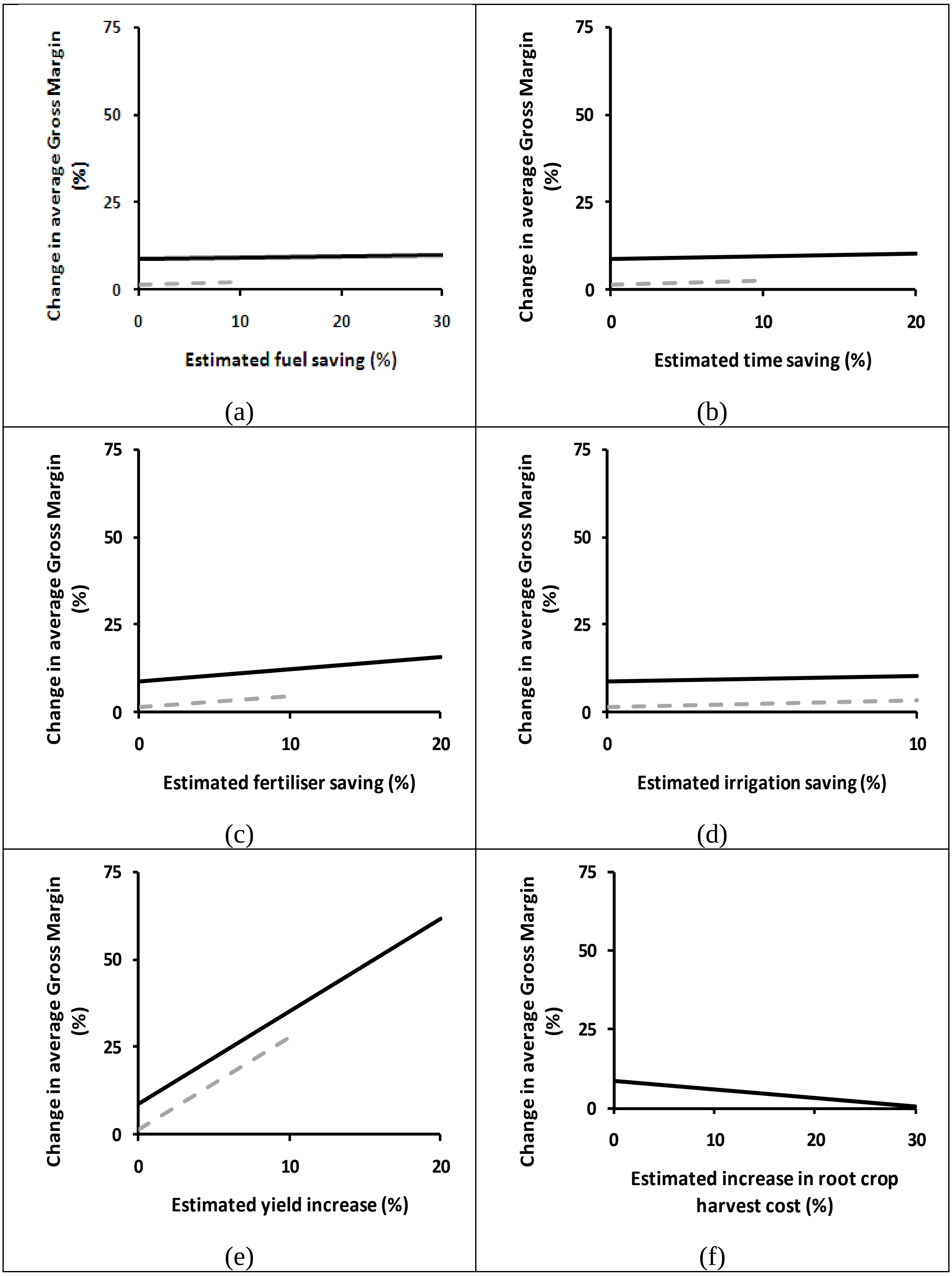
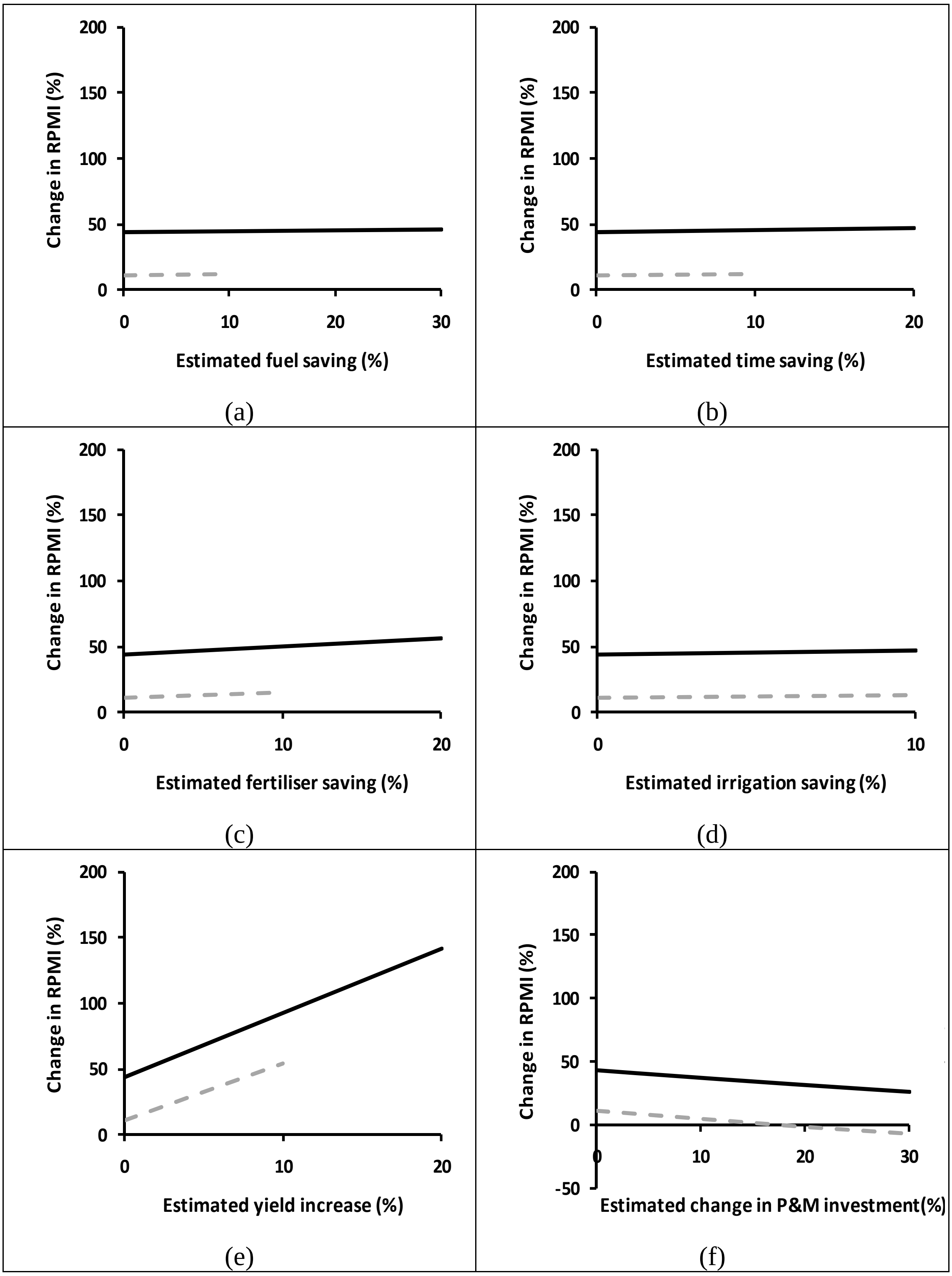
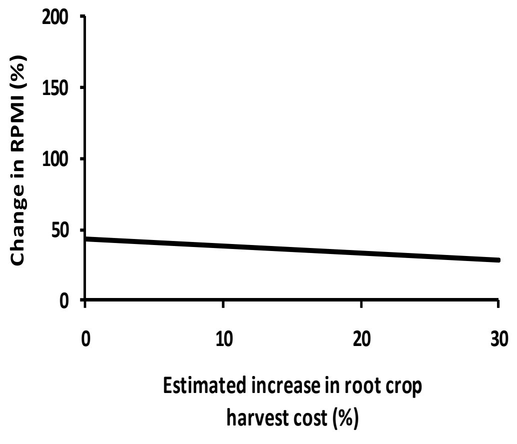


Figure 2. % change in average SCTF and CTF Gross Margin across a common rotation to changes in a range of variables, compared to the conventional system.

The very low slope of the line in Figure 2 (a) indicates that % change in Gross Margin is relatively insensitive to changes in fuel use. However, as noted above, the reduction in fuel use that occurs through changes in tractor inventory provides an immediate 8.7% increase in Gross Margin (as shown by the intercept on the y-axis), regardless of any other fuel savings that might occur through lighter workloads for the remaining tractors.

Another economic indicator of interest is the Return on Plant and Machinery Investment (RPMI) as described above. The response of RPMI to changes in the chosen variables is shown in Figure 3 (a – g).





(g)

Figure 3. % change in RPMI for SCTF and CTF systems across a common rotation to changes in a range of variables, compared to the conventional system.

Once again, it is noticeable from that there is an RPMI advantage for both SCTF and CTF even without any change in the chosen variables. In this case, this is a result of the changed equipment suite for SCTF and CTF, with fewer tractors required, and in particular, the removal of large tractors from the CTF inventory. Even the projected added cost of equipment modification is not sufficient to negate this advantage. The CTF equipment inventory would have to change from 15% below the conventional system (current estimate), to 8.5% above (a shift of 23.5%) in order to completely negate the inherent RPMI advantage of CTF. Root crop harvest costs under CTF would have to rise by 87% to have the same effect.

4.3.2.2 Sensitivity analysis, same rotation

Apart from providing indicators of actual economic returns in response to changes in the chosen variable, one value of a model is to identify those factors which have the greatest influence on the final result. Table 7 shows the ranking of the variables in decreasing order of economic significance. The measure of sensitivity is presented as the % change in Gross Margin and Return on Plant and Machinery Investment per % change in the relevant variable – effectively the slope of the response line, or in the case of negative responses, the absolute value of the slope.

Table 7. Sensitivity response – % change in Gross Margin and Return on P&M Investment per % change in variable

	Average gross margin over full rotation		**Return on Plant and Machinery investment**	
Variable	**SCTF**	**CTF**	**SCTF**	**CTF**
Crop yield	2.62	2.65	4.3	4.9
Fertiliser use	0.31	0.36	0.50	0.66
Irrigation water use	0.18	0.18	0.29	0.33
Time of working	0.12	0.09	0.20	0.16
Fuel use	0.07	0.04	0.11	0.07

Details related to the sensitivity of Gross Margin and RPMI to capital investment and root crop harvest costs are shown separately (Table 8) as they need additional explanation.

Table 8. Sensitivity response – % change in Gross Margin and Return on P&M Investment per % change in root crop harvest costs and plant and machinery investment

	Average gross margin over full rotation		Return on Plant and Machinery investment	
Variable	**SCTF**	**CTF**	**SCTF**	**CTF**
Plant and machinery investment			0.59	0.59
Root crop harvest cost		0.27		0.50

By definition, the calculation of Gross Margin does not include factors related to the capital investment in plant and machinery, so there is no sensitivity response to that factor. Capital investment clearly impacts on the RPMI, as shown in Table 8, being third behind yield and fertiliser use (Table 7) in its importance. The significance of this is two-fold:

1. it is important for growers not to over-invest in changes in technology, which is true regardless of the farming system used. Experiences in other industries suggest that modification costs for controlled traffic are more than offset by reductions in overall inventory. The fact that RPMI is sensitive to capital investment is hardly surprising, and also indicates that reductions in capital investment arising from controlled traffic adoption will offer a sizeable advantage, just as over-investment will have a negative impact.

2. from a modelling perspective, it is important to have reasonably accurate data on plant and machinery investment in order to generate reliable results from the model.

The cost of root crop harvest is the fourth most important variable tested in the model. While well behind yield in the sensitivity of its response, this indicates that it is important to address potential issues surrounding root crop harvest cost when considering controlled traffic adoption. While this issue may have a negative impact on both Gross Margin and RPMI, it can be easily offset by modest increases in yield. For example, it would require an increase in potato harvest cost of over 66% to negate a 10% potato yield increase. In the rotation used in this analysis, which included onions and potatoes, it would require an increase in potato and onion harvest costs of 115% to negate a 10% CTF yield increase across the rotation, and that is in the absence of any other potential CTF benefits.

4.3.2.3 Impact of a different rotation

For this scenario, the previously used rotation was maintained for the conventional and seasonal CTF systems. An alternative rotation was developed for the CTF system to capitalise on some of the projected benefits of the system (right hand column of Table 5). Once again, the variables (Table 3) were changed individually to determine their impact on the average Gross Margin per hectare over the full rotation. Selecting a rotation to make the best use of controlled traffic benefits does not change the overall trends or relativity of the impact on the variables used in the model. For each variable used in isolation, and in the absence of any yield benefit, the impact of the alternative CTF rotation is to increase the Gross Margin (CTF new rotation *cf* CTF old rotation) by 27% and the RPMI by 38%. The impact of the alternative rotation, without yield benefit, is shown in Figures 4 and 5. This highlights the potential of controlled traffic to provide more cropping opportunities, or the potential to grow more higher value crops (e.g. root vegetables) as the absence of compaction in the cropping zone may reduce the need for soil restitution crops, such as lower value cereal crops.

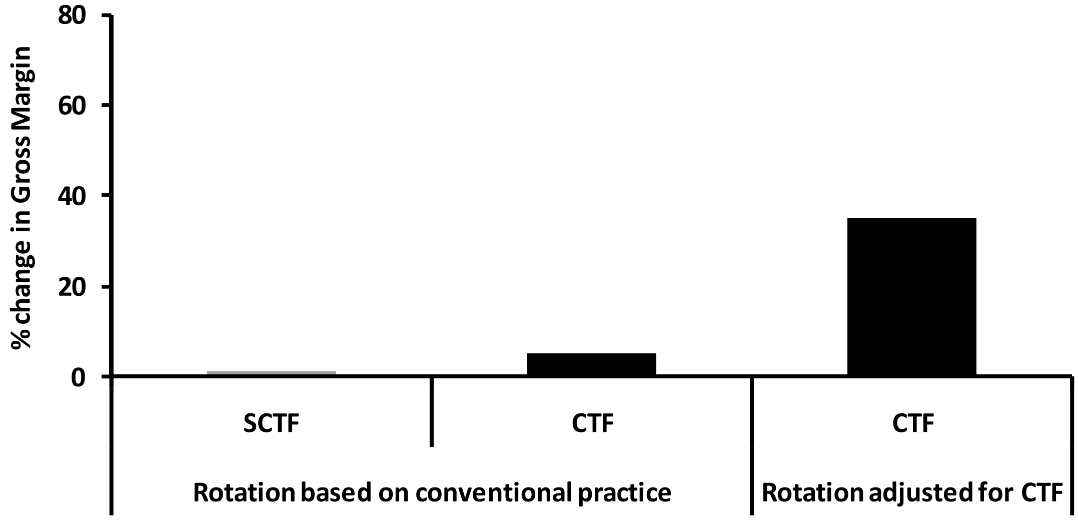


Figure 4. The response of Gross Margin to changes in rotation for CTF and SCTF systems, compared to conventional system.

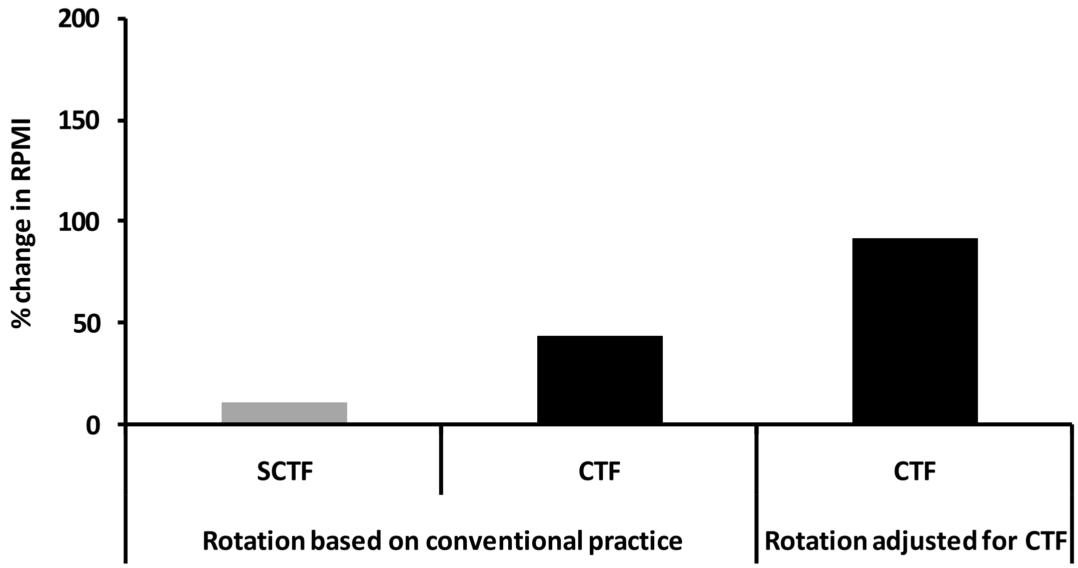


Figure 5. The response of RPMI to changes in rotation for CTF and SCTF systems, compared to conventional system.

4.3.2.4 Sensitivity analysis, different rotation

Sensitivity analysis conducted on the alternative rotation scenario did not alter the rank order of the variables, but it does impact on the sensitivity response. Table 9 shows the ranking of the variables in decreasing order of significance under the alternative rotation scenario.

Table 9. Sensitivity response – % change in Gross Margin and Return on P&M Investment per % change in variable for an alternative rotation for CTF

	Average gross margin over full rotation		Return on Plant and Machinery investment	
Variable	**SCTF**	**CTF**	**SCTF**	**CTF**
Crop yield	2.62	3.35	4.3	6.2
Fertiliser use	0.31	0.46	0.50	0.86
Irrigation water use	0.18	0.24	0.29	0.45
Time of working	0.12	0.09	0.20	0.16
Fuel use	0.07	0.04	0.11	0.08

Once again, the sensitivity results for capital investment and root crop harvest costs are shown separately in Table 10.

Table 10. Sensitivity response – % change in Gross Margin and Return on P&M Investment per % change in root crop harvest costs and plant and machinery investment for an alternative rotation for CTF

	Average gross margin over full rotation		Return on Plant and Machinery investment	
Variable	**SCTF**	**CTF**	**SCTF**	**CTF**
Plant and machinery investment			0.62	0.78
Root crop harvest cost		0.40		0.73

The conclusions arising from these results are no different to previously outlined. With the alternative rotation, yield is still the dominant variable influencing average Gross Margin and RPMI. The impact of yield is even higher under the alternative rotation scenario.

4.3.2.5 Impact of the system benefits of CTF

The results presented so far have outlined the response of Gross Margin and RPMI to the sequential alteration of a range of variables considered to be important influences on the economic performance of different cropping systems. Experience from other industries suggests that some of the major benefits of controlled traffic come from the system benefits – i.e. a number of changes, which may not necessarily be major in their own right, but collectively provided a major benefit.

On the basis of the limited information currently available, the model was run with a scenario judged to be an achievable “best bet”. The values of the variables used are detailed in Table 11. The rotation was also adjusted to take advantage of CTF benefits. Figures 6 and 7 show the results for change in average Gross Margin and RPMI for this scenario analysis.

Table 11. "Achievable" values of key economic factors used to compare conventional, SCTF and CTF vegetable production systems

	"Achievable" levels of change used in model compared to conventional practice	
	SCTF	CTF
Factor	Range used in model	Range used in model
Fuel use	10% reduction	20% reduction
Tractor time	10% reduction	20% reduction
Irrigation water use	0% reduction	0% reduction
Fertiliser use	0% reduction	0% reduction
Crop yield	5% increase	10% increase
Root crop harvest cost	0% increase	10% increase

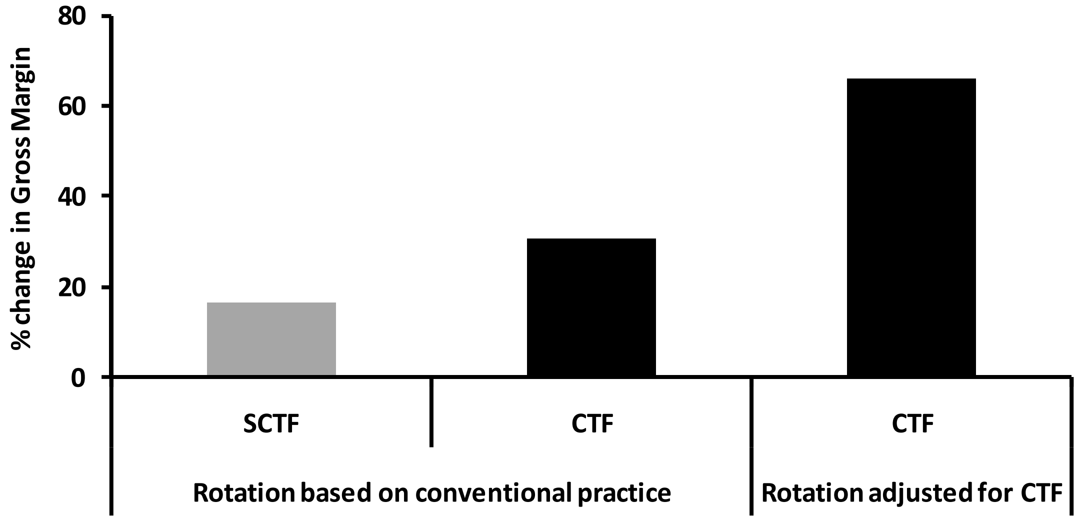


Figure 6. The response of Gross Margin to an "achievable" scenario for SCTF and CTF systems, compared to conventional system.

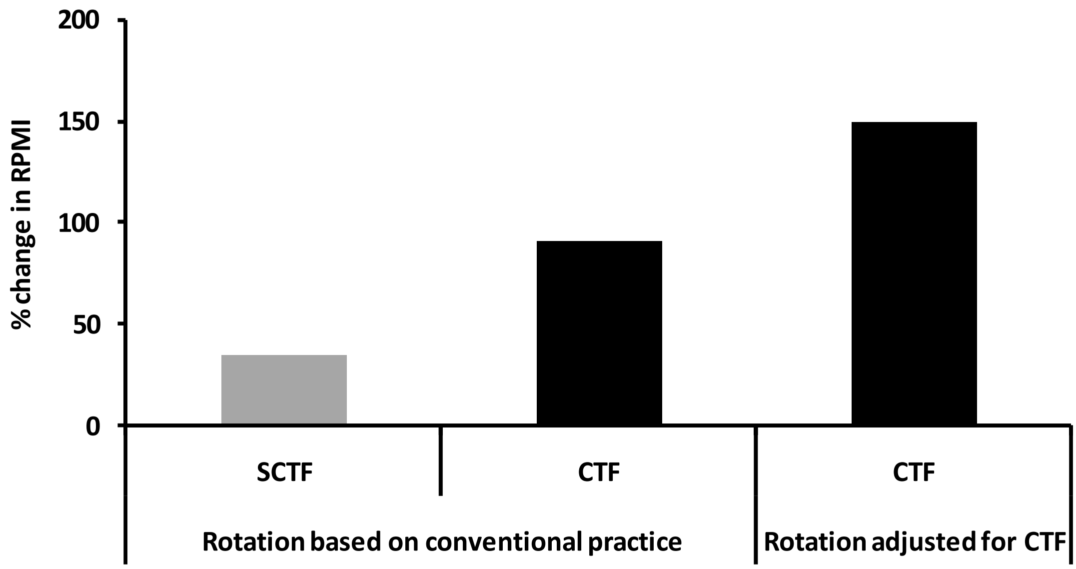


Figure 7. The response of RPMI to an "achievable" scenario for CTF and SCTF systems, compared to conventional system.

Tables 12 and 13 summarise the system impact of CTF on Gross Margin and RPMI, with the influences of yield separated and the "achievable" scenario displayed in separate columns.

Table 12. % Gross Margin changes (compared to conventional) arising due to rotational and "achievable" option differences

	no change to variables		"achievable option"	
Rotation	**SCTF**	**CTF**	**SCTF**	**CTF**
Same for all systems	2	9	16	34
Adjusted for CTF	2	38	16	66

Table 13. % RPMI changes (compared to conventional) arising due to rotational and "achievable" option differences

	no change to variables		"achievable option"	
Rotation	**SCTF**	**CTF**	**SCTF**	**CTF**
Same for all systems	11	44	35	91
Adjusted for CTF	11	98	35	150

4.3.2.6 Individual crop Gross Margins, "achievable" scenario

Figure 8 and Table 14 show the Gross Margins for all crops included in the model, not just those included in the rotation used for the analysis above. The graph is structured to show the conventional Gross Margin, and then the additional increase associated with SCTF and CTF systems.

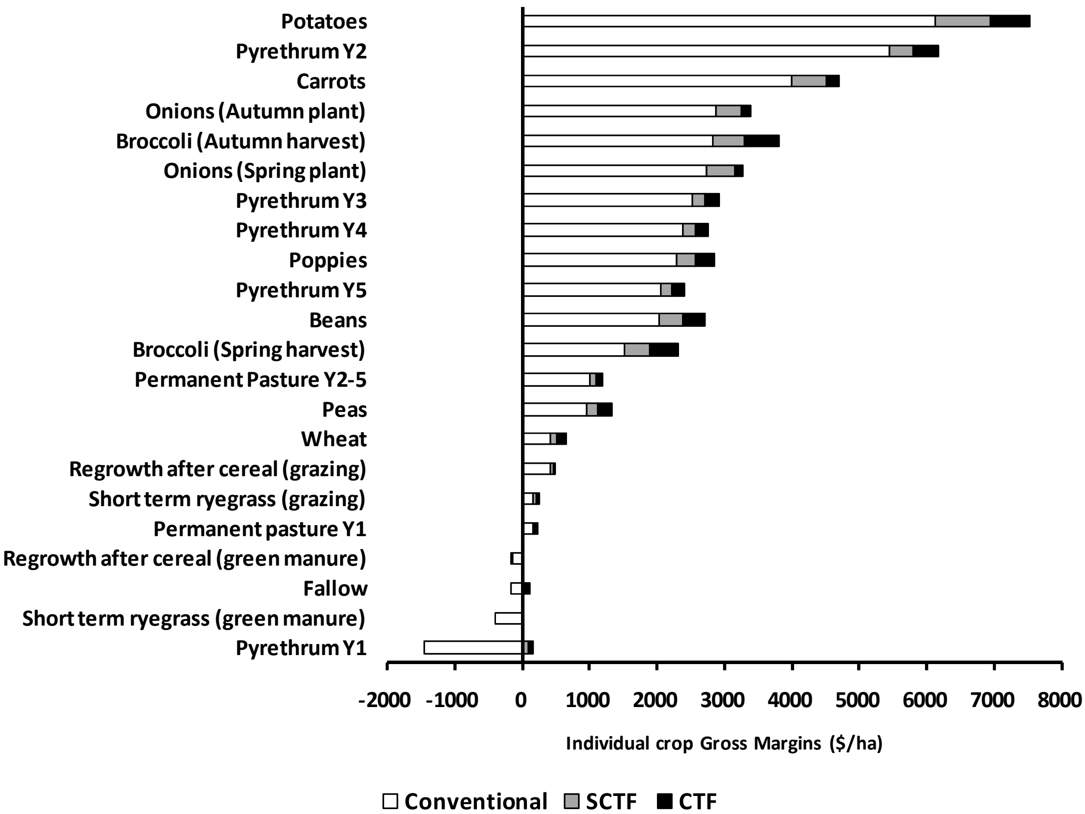


Figure 8. Gross Margins for all crops in the model for the "achievable" option, showing the Gross Margin for the conventional system, and the added benefit arising from SCTF and CTF.

Table 14. Gross Margin data ($/ha) for all crops in the model for the "achievable" scenario.

Crop	Conventional	SCTF	CTF
Potatoes	6,130	6,930	7,530
Pyrethrum Y2	5,430	5,800	6,180
Carrots	3,990	4,510	4,690
Onions (autumn planting)	2,870	3,250	3,390
Broccoli (autumn harvest)	2,830	3,290	3,800
Onions (spring planting)	2,730	3,150	3,270
Pyrethrum Y3	2,520	2,720	2,930
Pyrethrum Y4	2,380	2,570	2,760
Poppies	2,300	2,580	2,850
Pyrethrum Y5	2,050	2,220	2,400
Beans	2,040	2,380	2,710
Broccoli (spring harvest)	1,520	1,900	2,320
Permanent pasture Y2-5	1,000	1,090	1,190
Peas	960	1,120	1,330
Wheat	430	520	650
Regrowth after cereal (grazing)	430	450	480
Short term ryegrass (grazing)	170	200	240
Permanent pasture Y1	160	190	230
Regrowth after cereal (green manure)	-140	-140	-140
Fallow	-160	-110	-50
Short term ryegrass (green manure)	-390	-390	-380
Pyrethrum Y1	-1,460	-1,380	-1,300

4.4 Industry benefit

If the assumptions used in this analysis can be achieved, there will be substantial economic benefits on an industry-wide basis associated with the adoption of CTF. Estimating the increase in value for the whole vegetable industry that would come from adoption of CTF is a difficult task, as there are many variables which impact on such a result from year to year. A relatively simple approach has been taken in an effort to gauge the potential for increased industry-wide income.

Current areas of production for a range of crops in the north-west and midlands regions were collated from a range of statistical sources and local industry knowledge. Applying the Gross Margin figures for each crop and each management system allows an estimation of the total increase in value across all crops, regions and management systems.

In the first instance, these calculations were done assuming only the inherent advantages of SCTF and CTF were obtained. Next, the Gross Margins calculated for the "achievable" option previously modelled were used to estimate the gross industry change in value. However, one limitation of this analysis is that is includes the impact of benefits such as lower fuel use and increased crop yield, but does not include the impact of additional crops grown, as the Gross Margin calculations are on an individual crop basis. An attempt was made to accommodate this short-coming by increasing the area of one crop in each of the regions to reflect the assumptions that had been made in the "achievable" modelling scenario. For the north-west, this crop was potatoes, and for the midlands, it was autumn harvest broccoli. Table 15 outlines the projections calculated by the above process. The % gain over current value is given in parentheses next to each figure.

Table 15. Projected industry-wide increases in gross crop return ($m/y) and % increase over current value (in parentheses) due to adoption of SCTF and CTF

	SCTF	CTF
no variables changed	1.1 (1.3)	3.2 (3.6)
"achievable" scenario, without extra crops	11.3 (13)	21.5 (24)
"achievable " scenario with CTF adjusted rotation		26.2 (29)

The value in this exercise is not so much about trying to arrive at an accurate figure for increased value of production, but more to indicate that, provided the benefits of CTF can be captured, there will be significant return to the industry to fund the mechanical changes required. It is unlikely that a wholesale, rapid change to CTF will occur, so an increase in returns is not likely to be immediate. However, if even a portion of the projected increased valued outlined in Table 15 was to be generated annually, it would indicate that a move to CTF would be a valuable change.

This also raises the question of how best to proceed with a transition to CTF. A feature of the Tasmanian vegetable industry is its high reliance on contractors, particularly in the area of harvest, but increasingly in other aspects of the production cycle, such as tillage, sowing, transplanting and spraying. In some cases, particularly in situations requiring expensive, dedicated harvesters (e.g. peas, beans, poppies, carrots) the equipment is owned by the company for whom the product is grown.

On the basis of a simple Gross Margin analysis, the grower is the key beneficiary of improved returns. However, those improved returns can only be captured through changes made in all sectors of the industry, and in many cases, the major investments in the change will be made by contractors. This is an issue which the industry as a whole needs to consider in terms of how best to progress with controlled traffic adoption, and the equitable sharing of the costs and benefits.

4.5 GHG emissions

Greenhouse gas emissions estimated with the model are categorised as follows:

1. Average farm GHG emissions, comprised of
    a. Average soil GHG emissions
    b. Average fuel GHG emissions
2. Average manufacturing GHG emissions, and
3. Average farm and manufacturing GHG emissions, the sum of categories 1 and 2 above.

GHG emissions are all expressed as kg CO_2-e per hectare across the full rotation. Only results from the north-west coast modelling are reported, as the trends and implications for the midlands farm are consistent with these results.

4.6 GHG emissions analysis

4.6.1 Initial impact of SCTF and CTF

As with the economic analyses, there is an inherent beneficial impact of adopting SCTF or CTF on the calculated GHG emissions. This comes about because of two factors:

- Reduced fuel use under the controlled traffic scenarios
- Reduced soil emissions due to better drained soil conditions, leading to reduced time for generation of nitrous oxides.

The existence of this inherent benefit is apparent in the data presented in the following sections. In all cases, all of the variables used in the model were set at zero, so any differences arising in the output are purely due to the in-built differences between the management systems.

4.6.2 Impact of varying fuel and fertiliser use

Fuel and fertiliser are the two main production inputs that affect the level of GHG emissions calculated by the model. As noted previously, both of these have a large initial influence on GHG emissions through the adoption of CTF, fuel because of fewer and smaller tractors, independent of any other savings, and fertiliser because of beneficial changes in soil condition. Changing management systems also offers the opportunity for further savings in fuel and fertiliser, although the additional influence of these savings is much less than the underlying impact of the change of system. The range of reductions in GHG emissions for each of the categories, as a result of adopting SCTF and CTF, and as a result of adjusting variables in the model, is given in Table 16.

Table 16. Reductions in GHG emissions by category due to the adoption of SCTF and CTF, and adjustment of input variable.

GHG category	SCTF	CTF
Fuel	10% – 15%	31% – 40%
Soil	31% – 36%	67% – 73%
Total farm	27% –30%	59% – 64%
Manufacturing	2% – 7%	3% – 16%
Total	21% – 25%	47% – 54%

Table 17 shows the sensitivity of the various GHG emissions categories to changes in the variables of fuel and fertiliser. One of the most important is the impact on manufacturing emissions in relation to fertiliser use, reflecting the well recognised energy intensiveness of nitrogen fertiliser production.

Table 17. Sensitivity response – % change in calculated GHG emissions per % change in fuel and fertiliser use for SCTF and CTF for the same rotation across all management systems

	Fuel use		Fertiliser use	
GHG category	SCTF	CTF	SCTF	CTF
Fuel	0.53	0.32		
Soil			0.49	0.33
Total farm	0.11	0.07	0.38	0.26
Manufacturing	0.04	0.02	0.56	0.66
Total	0.10	0.06	0.42	0.35

4.6.3 Sources of GHG emissions

Three categories of emissions contribute to the total emissions associated with the different farming systems – soil and fuel emissions on farm, and manufacturing emissions pre-farm. Table 18 indicates the approximate contribution each of these categories makes to the total emissions for the three farming systems under consideration.

Table 18. % contribution of various sources of GHG emissions for different management systems

GHG source	Conventional	SCTF	CTF
Soil	62	55	38
Fuel	16	18	22
Manufacturing	22	27	40

The ratios vary by no more than a few percent, regardless of the rotational system used, or the projected changes in greenhouse related inputs (i.e. fuel and fertiliser). Based on the assumptions used in this model, it is clear that soil emissions arising from the use of nitrogen fertiliser are a key component of the total emissions. This is in broad agreement with the findings reported in the final report of project PT07060 – Enhancing environmental sustainability in the processing potato industry in Australia (Norton *et al.*, 2008). It is also clear from Table 18 that the changes to soil conditions under CTF have the potential to significantly reduce the soil emissions contribution.

Figures 9 and 10 show the calculated GHG emissions for the total farm and total farm + manufacturing across all crops in the model. The graphs are structured to show the CTF emissions, and then the additional increase associated with SCTF and conventional systems. The data presented are for the three different management systems, without any changes applied, apart from the inherent changes that occur with the adoption of SCTF and CTF – i.e. fuel reduction on account of fewer and smaller tractors used.

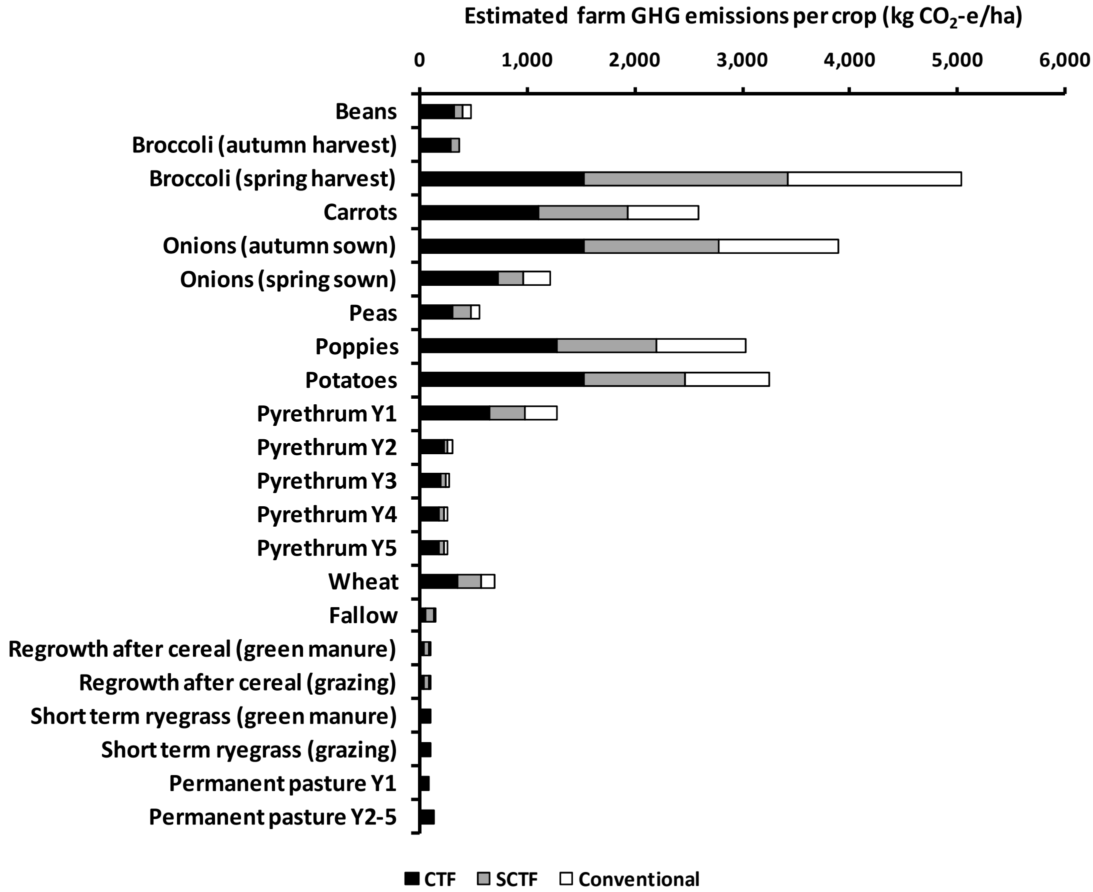


Figure 9. Estimated total farm GHG emissions for each crop used in the model.

The crops with the highest emissions in Figure 9 tend to be those that have fertiliser applied during winter or early spring, when soil is moist, and there is the highest risk of high water filled pore space, which is an important factor in nitrous oxide production.

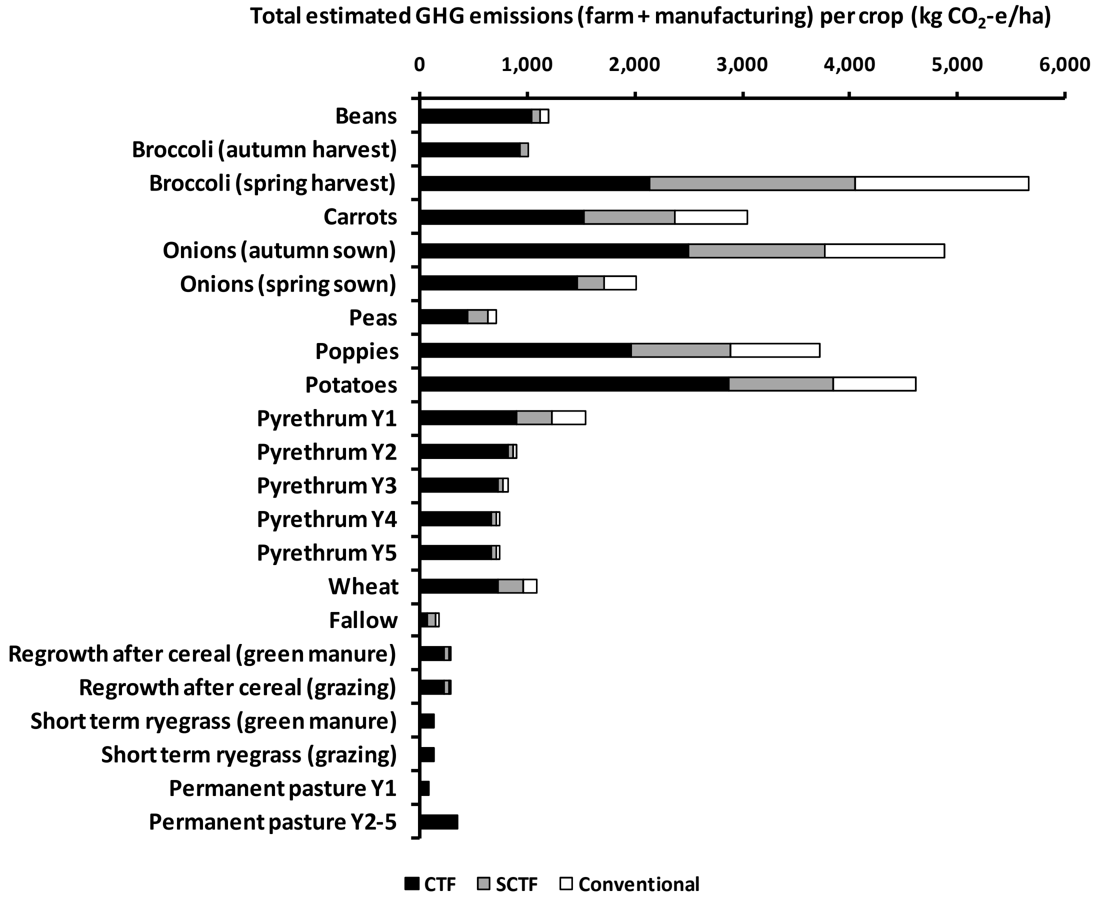


Figure 10. Estimated total GHG emissions (farm +manufacturing) for each crop used in the model.

4.6.4 Impact of "best bet" rotation on GHG emissions

The "best bet" rotation would be expected to increase the GHG emissions for the CTF system, as the alternative rotation allows for an extra crop in the same time period, with the addition of the relevant fuel and fertiliser GHG contributions. The calculated increase in GHG emissions as a result of altering the rotation to favour CTF is shown in Table 19.

Table 19. % increase in calculated GHG emissions for a CTF adjusted rotation compared to CTF used for the original rotation

Soil	Fuel	Total farm	Total farm + manufacturing
12	17	14	14

4.7 Sensitivity of modelling assumptions for soil emissions

The model calculates soil emissions of greenhouse gases based on some known inputs and some assumptions, as follows:

- Nitrogen fertiliser use
- % of paddock area that is wheeled
- IPCC emissions factor
- Difference in emissions due to broadcast or drilled fertiliser placement
- Number of days the soil contains nitrogen in excess of crop requirements

- % of wet days during the excess nitrogen period that generate conditions of high Water Filled Pore Space
- % of days that high Water Filled Pore Space is maintained in the wheeled area
- % of days that high Water Filled Pore Space is maintained in the non-wheeled area

The rationale for use of these factors is outlined in Section 3. Of all the factors listed above, the only one that is known with any degree of accuracy is the amount of nitrogen applied to the crop. The IPCC emissions factor is referenced in the climate change literature [1], but other researchers have observed emissions levels which suggest alternative factors may be appropriate in some conditions (Ruser *et al.,* 1998).

As this part of the model includes many factors which vary based on the assumptions used, it is important to understand the significance of each factor in terms of its influence on the output. The sensitivity of the output was tested by varying each of the factors listed above by 50%. The sensitivity factors in Table 20 were derived from the % change in emissions per % change in the variable in the left-most column.

Table 20. Rank order of sensitivity of calculated soil GHG emissions to variables used in the model

Soil GHG	Sensitivity		
	Conventional	**SCTF**	**CTF**
Days excess N	1.00	1.01	1.04
% wet days with high WFPS	1.00	1.01	1.04
IPCC factor	1.00	1.00	1.00
% days high WFPS wheeled area	1.00	0.95	0.78
Broadcast/drilled ratio	0.33	0.34	0.28
% wheeled area	0.00	0.84	0.67
% days high WFPS non-wheeled area	0.00	0.05	0.25

The rankings in Table 20 indicate the need for more accurate knowledge in four key areas:

- Number of days the soil contains nitrogen in excess of crop requirements
- % of wet days during the excess nitrogen period that generate conditions of high Water Filled Pore Space
- IPCC emissions factor
- % of days that high Water Filled Pore Space is maintained in the wheeled area

In addition, the model indicates that the % wheeled area is important, having implications for how much the wheel track area can be reduced under CTF. As far as the modelling is concerned, this figure can be estimated reasonably accurately based on machinery configurations used in CTF, although it is more difficult to estimate the impact of wheel area in the SCTF system.

4.8 Conclusion

4.8.1 Economics

Although this analysis has relied on a range of assumptions drawn both from current limited experience in the vegetable industry, and more extensive experience and data from other industries, it is clear there is considerable economic potential to be gained from CTF, both at the individual farm level and across the industry. The true quantum of benefits will not be determined until there is more adoption of controlled traffic in the vegetable industry, and it is possible to do retrospective economic analyses.

However, the modelling offers some useful insights, highlighted below.

- Based on the assumptions used in this model, it was possible to reduce total capital investment in plant and machinery, which includes irrigation equipment, for a north-west coast vegetable farm by 5% for SCTF and 15% for CTF, compared to the conventional system. If applied only to the tractor and implement component of the plant and machinery, the reductions were 11% and 35%, respectively. The comparative figures for a midlands farm were 7.5% and19% for the overall plant and machinery investment, and 16% and 42% when applied only to the tractor and implement component.
- Adopting CTF, without capturing any of the potential system benefits, provided an 8.7% increase in Gross Margin and a 44% increase in RPMI over the conventional system for a north-west farm. For the midlands example, the comparative figures were 9.3% and 63%.
- Yield is the most important variable contributing to improved Gross Margins and RPMI. While data is limited for vegetables, research and commercial experience over a wide range of industries indicate that a 10% yield increase per crop should be achievable under a fully integrated CTF system. In the absence of changes to any other variable, for a north-west farm, such an increase provided a 31% improvement in Gross Margin and a 85% increase in RPMI, compared to the conventional system.
- The equivalent results for a midlands farm were a 31% improvement in Gross Margin and a 112% increase in RPMI, compared to the conventional system.
- CTF may provide opportunities to intensify the crop rotation due to better soil conditions. A more intense rotation on a north-west farm, without yield benefit, increased Gross Margin by 35% and RPMI by 92%, compared to the conventional system.
- When the same conditions were applied to the midlands farm scenario, a more intense rotation, without yield benefit, increased Gross Margin by 27% and RPMI by 102%, compared to the conventional system.
- Fertiliser is the most important of the variable inputs. It ranks about equal with root crop harvest costs in its impact on Gross Margins for CTF, and .plant and machinery investment in its impact on RPMI for SCTF and CTF.
- A scenario believed to be “achievable” was modelled for each of SCTF and CTF for both the north-west and midlands farm situations. This scenario incorporated extra fuel and time savings, improved yield, and a different rotation and a slight increase in root crop harvest costs for CTF. For the north-west situation, the Gross Margin increases were 16% and 66% for SCTF and CTF, respectively. The accompanying RMPI increases were 35% and 150%. The equivalent results for the midlands farm were 15% and 56% for SCTF and CTF Gross Margins, and 43% and 167% for the respective RPMI increases.

There are clear economic benefits to be gained from the adoption of controlled traffic. These have not yet been attained in commercial practice due to the complexity of the vegetable industry machinery environment. An analysis of the potential return on an industry-wide basis provides some insight into the level of investment that could be warranted in order to obtain the benefits of CTF.

4.8.2 Industry benefit

There are potentially very significant production and economic benefits to be gained on an industry-wide basis through the adoption of CTF. Many variables impact on the quantum of benefit that will eventually be achieved. A simple approach of applying the Gross Margin gains produced through modelling to annual estimates of crop area shows potential annual gains ranging from $3 m - $26 m. The wide range reflects the range of potential benefit capture, and the reality is likely to be somewhere in the middle.

The value in trying to estimate the industry wide economic benefit is less about the true extent of the actual increased value, but more about indicating that there are significant gains to be made if the benefits of CTF can be captured.

4.8.3 GHG emissions

Nitrogen fertiliser use, with a significant manufacturing energy component and significant soil emissions potential, is the most important input variable in terms of GHG emissions. Considering all sources of GHG emissions, there was a reduction in farm-based emissions of 26% through the adoption of SCTF, and 60% due to CTF.

For a north-west coast farm scenario, a rotation selected to make best use of the CTF opportunities increased CTF emissions by about 14% compared to the common rotation, largely as a result of additional crops being added to the rotation. Such a choice also adds extra fuel and fertiliser requirements.

Apart from the level of reductions indicated by the model, the far more important result of this part of the modelling is identification of the key variables which influence the level of emissions. The calculations used in this model are based on the evidence that soils which are compacted are more likely to experience high water filled pore space following rain, conditions which favour the production of nitrous oxides. Controlled traffic has the capacity to reduce this risk.

Sensitivity analysis shows there are three key assumptions about soil conditions that require improved data in order to more reliably predict GHG emissions under these scenarios:

- Number of days the soil contains nitrogen in excess of crop requirements
- % of wet days during the excess nitrogen period that generate conditions of high Water Filled Pore Space
- % of days that high Water Filled Pore Space is maintained in the wheeled area

In addition, it is important for there to be confidence in the IPCC emissions factor used in calculations, as this has a significant influence on the estimation of GHG emissions from this model. This has particular relevance in the controlled traffic situation, as emissions factors calculated from research in random traffic management systems are unlikely to be applicable to the soil conditions that exist under controlled traffic management.

5. Discussion

5.1 The model and modeling

An economic model was developed to represent farming systems within the Tasmanian vegetable industry. A base model was developed for a large north-west coast farm, and then modified to represent a farming operation in a different location (i.e. northern midlands of Tasmania). A basic greenhouse gas emissions model was integrated with the economic model. The Gross Margin and GHG components of the model were replicated and adjusted to represent farming systems based on conventional practices, seasonal controlled traffic and fully integrated controlled traffic.

A range of variables were chosen for adjustment to determine the economic and GHG impact of changing farming systems. A range of assumptions were used based on current limited experience with CTF in the vegetable industry, and experiences from other industries and parts of the world. The assumptions used are well within the realms of possibility when using a fully integrated controlled traffic system, and when modelling “best bet” scenarios, the assumptions have tended towards being conservative.

5.2 Economics

As part of the modelling, vegetable production inputs were adjusted over a wide range to determine the relative importance of each variable. Although changing to SCTF or CTF provides opportunities to reduce capital and operating costs, the dominant influence on the economics of vegetable production is crop yield. In the interests of conciseness, the discussion here relates only to the “best bet” scenario that was modelled for inclusion in this report.

The “best bet” scenario for CTF was structured towards being conservative. Nevertheless, the economic results for this scenario, compared to the base conventional system, are significant, with Gross Margin increases across the whole rotation of 16% and 66% for SCTF and CTF, respectively, and accompanying RPMI increases of 35% and 150%. When a similar scenario was applied to the midlands farm model, the average Gross Margin across the rotation increased by 15% for SCTF, and 56% for CTF. The accompanying RPMI increases were 43% and 167%.

These results are very much influenced by increased yield and the assumption that an alternative rotation will be possible when using CTF. Therefore it is clear that these opportunities must be realised to capture the full potential of CTF.

Aside from yield, other factors with a key influence on the final economic performance include fertiliser use, capital investment in plant and machinery, and the costs of root crop harvest. While plant and machinery capital investment is likely to be less for controlled traffic, there is the possibility that root crop harvest costs could increase due to more constraints on traffic movements. However, a modest yield increase would be more than enough to offset any predictable increase in harvest costs.

Of the crops included in the north-west coast model farm rotation, potatoes return the highest Gross Margin under CTF, followed by second year pyrethrum, carrots and autumn sown onions. Spring harvest broccoli provides the biggest potential % increase in return as a result of adopting CTF. The highest Gross Margin crops for the midlands farm were potatoes, autumn harvest broccoli and spring sown onions.

5.3 Industry-wide benefits

At an industry-wide level, there are potentially very significant economic benefits to be gained from a transition to controlled traffic. Although there are many factors which determine the value to be returned from investment in the change to controlled traffic, a simple analysis based on current estimates of cropped area and the projected improvements in Gross Margin for each crop suggests there are potentially large increases in revenue to be gained. With the potential to provide improvements in overall efficiency and sustainability, controlled traffic could be a significant contributor to the capacity of the industry to increase its production capacity and to withstand external pressures, such as the increasing volume of imported products.

5.4 Greenhouse gas emissions

Controlled traffic farming systems are of interest and relevance to the current debate about agricultural greenhouse gas emissions and climate change adaptation. Nitrous oxides are one of the key greenhouse gases relevant to agriculture. There is sound evidence that soil conditions created by controlled traffic have the potential to significantly reduce nitrous oxide emissions from nitrogenous fertilisers.

This evidence was the basis of the GHG emissions component of the model. The results from the model indicate that controlled traffic has the potential to significantly reduce farm-based emissions. However, more important is the identification of a number of factors that are relevant to the final calculated result.

One of the key drivers of nitrous oxide emissions is the combination of nitrogen supply in excess of plant needs and high water filled pore space in the soil. In the absence of accurate data, a range of assumptions were made about these factors based on local knowledge, observation and experience. However, there are some key questions to be answered in order to provide a greater degree of confidence to the results generated by the model. These include:

- What is the critical % water filled pore space for rapid nitrous oxide production?
- How long does it take conditions of high water filled pore space to change under a range of soil and climatic conditions, including the differences between conventionally and CTF managed soils?
- What is the time period of excess nitrogen for different crops, seasons and application methods?

The model as developed focused entirely on the emissions side of the greenhouse gas issue. Sequestration was not included, as it is even more complex than emissions. However, it should be noted that if increased yields are a feature of CTF systems, then so is increased biomass production. While crop residues may not be a significant contributor to soil carbon in vegetable production systems, producing and returning more biomass to the soil can only benefit soil carbon, not detract from it.

The potential environmental benefits offered by CTF are many, and intuitively not difficult to identify. However, robust analysis of the true quantum of these benefits has hardly begun in the context of the vegetable industry.

At this stage, agriculture is not included in any of the proposed carbon reduction mechanisms proposed by the Federal Government. Therefore, although growers will inevitably face increased costs due to higher input costs, there will be no cost penalty associated with farm-based emissions, nor will there be any significant income to be made from reducing emissions or sequestering carbon.

6. Technology transfer

6.1 Field days and meetings

- Poppy Productivity Expo, Moriarty, 2 June 2011
- TIAR Vegetable Centre Industry Communication Forum, Longford, 14 July, 2011
- Grower group discussion, Sister's Creek, 18 August, 2011
- Simplot meeting, Devonport, 25 August, 2011

There have been many extension activities related to controlled traffic in the Tasmanian vegetable industry during the life of this project. While these were not all specifically related to this project, they have provided opportunities to increase awareness and information transfer about this project as part of the broader discussion around controlled traffic development and adoption.

6.2 Media

As the modelling work was completed late in the life of the project, there has been very little exposure for the project in the media. With initial results providing a very favourable indication of the economic value of controlled traffic, some media exposure will be arranged on completion of the project.

6.3 Future events

Extension and industry engagement activities related to controlled traffic are on-going in the Tasmanian vegetable industry across a number of projects. The models developed as part of this project will be used in conjunction with grower meetings and discussions, as well as with industry groups, over the coming months as part of a broader awareness about controlled traffic adoption in the vegetable industry in Tasmania.

7. Recommendations

7.1 Situation summary

The benefits of controlled traffic farming (CTF) have been established through research over the last 40 years, and more recently through commercial adoption, particularly in the Australian grain and cane industries. Controlled traffic, in the form of permanent beds, is already adopted by a small number of growers in some sectors of the vegetable industry, primarily those which have very simple mechanisation requirements. This is the case in some areas for melon and leafy greens production.

The mechanisation requirements of other parts of the vegetable industry, in particular for crops such as potatoes, carrots and onions, makes the integration of controlled traffic more difficult. The situation is further complicated because many vegetable growers, particularly in Tasmania, also grow crops that are more broadacre in nature, such as poppies, pyrethrum and cereals. This diverse mix of crops means the equipment mix in the industry is equally diverse, and 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.

7.2 Economic potential

The modelling undertaken for this project clearly indicates there are substantial economic gains to be achieved through the adoption of controlled traffic in the vegetable industry. At the individual farm level, these gains can be achieved through some capital cost savings, operational savings, and most importantly, improved yield.

At a broader industry level, the economic benefits are also substantial. One of the features of the Tasmanian vegetable industry is the widespread use of contractors for many crop production tasks, particularly harvest. This presents a key industry challenge, as integration of harvest equipment is one of the key challenges to CTF adoption. It means that, while many of the economic benefits of CTF adoption flow to the grower, a substantial portion of the costs will be borne by the contractor. This is an issue that needs addressing in order for all participants in the industry to benefit from such a fundamental change to the production system.

7.3 GHG emissions

In addition to economic benefits, there are clearly a number of environmental benefits associated with the adoption of controlled traffic, not least of which is a reduction in GHG emissions. The science surrounding this is open to much debate and conflicting evidence. Nevertheless, an attempt has been made to model some of the GHG emission factors that are relevant to comparing conventional, SCTF and CTF systems. A key need is to undertake more research into the in-field impacts of traffic and tillage management on soil GHG emissions, particularly in relation to the soil physical differences that arise through the use of controlled traffic.

7.4 Industry adoption of SCTF and CTF

While there are many challenges to implementation of controlled traffic in the vegetable industry, highlighting the economic potential will hopefully encourage some interest and action from growers and industry groups to indentify steps that can be taken to progress adoption. SCTF would be a valuable starting point for the vegetable industry, given the complexity of the harvester integration issue. SCTF should be a relatively easy step for the industry to make. All it requires is the use of satellite guidance and adoption of a common wheel track width and modular implement widths.

7.5 Future project recommendations

The development of an economic model to accommodate the changes that are likely to occur under SCTF and CTF provides a tool for the industry to use to assess the likely benefits of a change to controlled traffic. Although the model has not yet seen widespread industry exposure, it will be used in various forms over the coming months to demonstrate the economic potential of controlled traffic. However, it has already identified a number of areas that are important in the context of economic benefits arising from CTF, and these are proposed as possible future areas of research:

- *Yield* – as increased yield is one the most important aspect of improved economic performance, some research should be devoted to specifically investigate the yield potential of controlled traffic systems. Although there are other projects in place (MT09040 – "Development and demonstration of controlled traffic farming techniques for production of potatoes and other vegetables" and VG10080 – "On-farm demonstration of CTF for vegetables") which are addressing some of the developmental and soil change issues related to controlled traffic, none is looking specifically at yield in the absence of traffic.
- *Fertiliser* – given the influence of fertiliser on the economics of vegetable cropping, there is also the opportunity to investigate whether or not the improved soil conditions of controlled traffic lead to improved fertiliser use efficiency. Research of this nature could be integrated with the topic above.
- *Spatial arrangements* – because there has never before been a need to accommodate crops within an industry-wide track and implement width combination, a move to controlled traffic may require altered spatial arrangements for some crops (e.g. potatoes). In combination with yield and fertiliser research, some attention needs to be given to spatial arrangements for optimisation of yield and mechanisation under controlled traffic.
- *Soil impacts on GHG emissions* - a number of key questions need to be resolved regarding the changes in soil conditions under CTF and how they affect GHG emissions, particularly in relation to soil moisture and porosity, and the generation of nitrous oxides.

7.6 Recommendation

There is substantial interest in the development of controlled traffic in the vegetable industry, and activities are occurring on many fronts. Current projects are attempting to deal with some of the implementation issues of the system. There is a need for investment to support work to encourage adoption at the farm and industry level. There is also a need for additional research to quantify some of the production and environmental benefits to fully capture the potential of controlled traffic farming in the vegetable industry.

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11. Appendix A

11.1 Midlands large farm model

The model was adjusted to reflect crop rotation and equipment options for a large midlands farm, also with an area of 270 ha of vegetable and associated crops. Two cropping options were considered, one which included potatoes and one which did not. Only results from the rotation including potatoes are presented here.

11.1.1 Equipment investment

The capital cost of the equipment suite, including irrigation infrastructure, for the midlands farm reduced by 7.5% for SCTF and 19% for CTF. If considering only the tractor and implement part of the plant and machinery suite, the reductions in capital are 16% and 42% for SCTF and CTF, respectively.

11.1.2 Economic analysis

11.1.2.1 Impact of individual parameters, same rotation

As outlined in Section 3.2.2., a common rotation was used for all management systems, and the variables were changed individually to generate the results. The responses of Gross Margin and RPMI to changes in the chosen variables followed the same pattern as for the north-west coast farm model. For the base rotation, the inherent advantage of CTF in the midlands resulted in a 9.3% improvement in Gross Margin and a 63% improvement in RPMI.

11.1.2.2 Sensitivity analysis, same rotation

Table 21 shows the significance of the variables, calculated as the % change in Gross Margin and Return on Plant and Machinery Investment per % change in the relevant variable.

Table 21. Sensitivity response – % change in Gross Margin and Return on P&M Investment per % change in variable, midlands model

	Average gross margin over full rotation		**Return on Plant and Machinery investment**	
Variable	**SCTF**	**CTF**	**SCTF**	**CTF**
Crop yield	2.17	2.17	4.2	4.8
Fertiliser use	0.39	0.39	0.75	0.86
Plant and machinery investment			0.73	0.72
Root crop harvest cost		0.22		0.48
Time of working	0.12	0.09	0.23	0.20
Irrigation water use	0.08	0.08	0.15	0.17
Fuel use	0.06	0.04	0.13	0.10

In the case of the midlands model and the chosen rotation, plant and machinery investment and root crop harvest costs rank behind fertiliser use for their impact on Gross Margin and RPMI, respectively. Once again, the negative impact of potential increases in root crop harvest cost can be offset by modest increases in yield. In the rotation used in this analysis, which included onions and potatoes, it would require an increase in potato and onion harvest costs of 130% to negate a 10% CTF yield increase across the rotation.

11.1.2.3 Impact of a different rotation

An alternative rotation was developed for the CTF system which allowed a quicker return to cash cropping, rather than a lengthy phase in pasture to allow soil remediation. The details of the rotations are shown in Table 6, Section 3.2.2. The impact of the alternative rotation, without yield benefit, is shown in Figures 11 and 12, highlighting the potential of controlled traffic to provide more cropping opportunities.

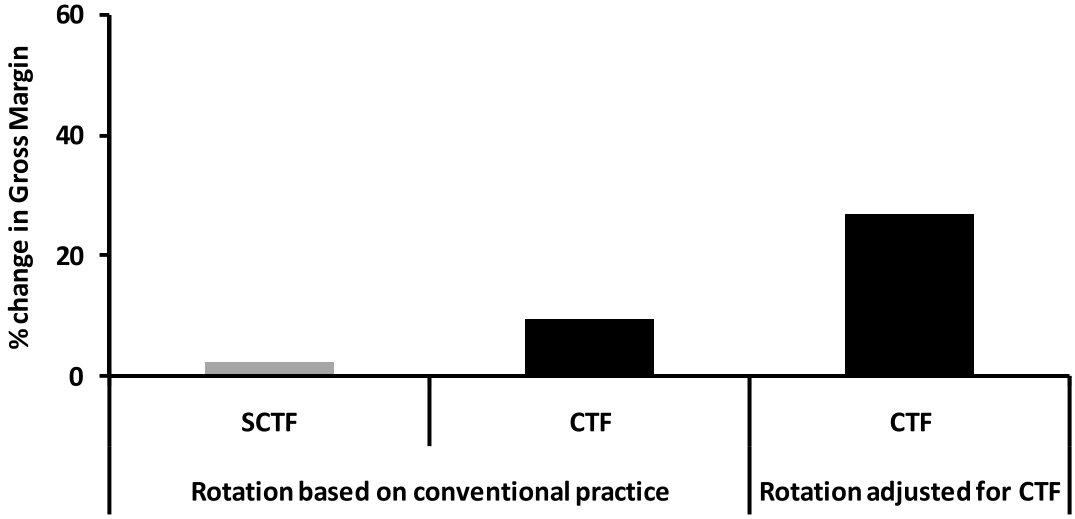

Figure 11. The response of Gross Margin to changes in rotation for CTF and SCTF systems, without any yield benefit, compared to conventional system.

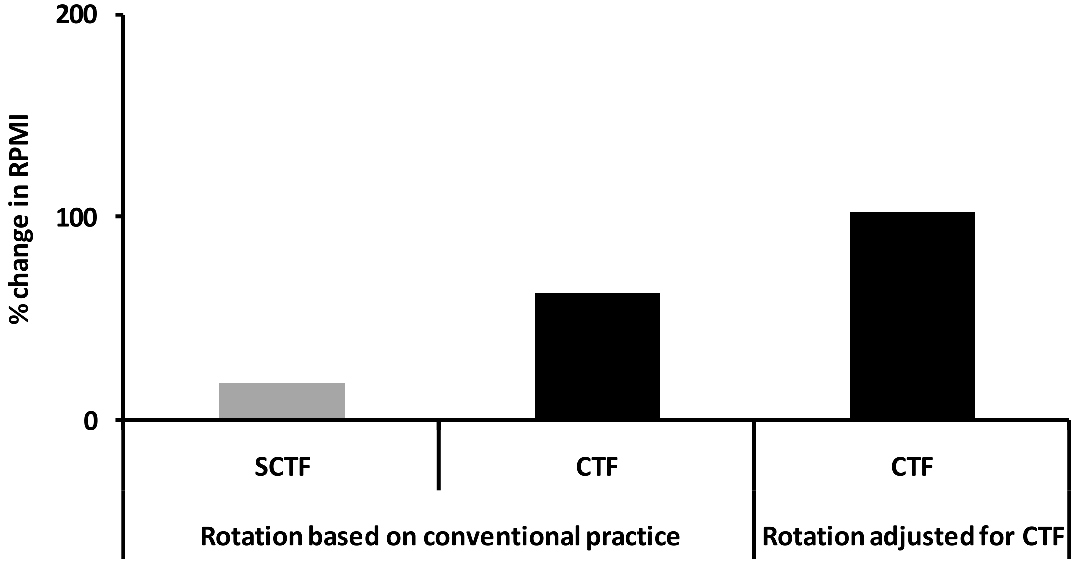

Figure 12. The response of RPMI to changes in rotation for CTF and SCTF systems, without any yield benefit, compared to conventional system.

11.1.2.4 Sensitivity analysis, different rotation

Sensitivity analysis conducted on the alternative rotation scenario did not alter the rank order of the variables, but it does raise the importance of yield as a contributing factor. Table 22 shows the ranking of the variables in decreasing order of significance under the alternative rotation scenario.

Table 22. Sensitivity response – % change in Gross Margin and Return on P&M Investment per % change in variable for an alternative rotation for CTF

	Average gross margin over full rotation		**Return on Plant and Machinery investment**	
Variable	**SCTF**	**CTF**	**SCTF**	**CTF**
Crop yield	2.62	3.35	4.3	6.2
Fertiliser use	0.31	0.46	0.50	0.86
Plant and machinery investment			0.62	0.78
Root crop harvest cost		0.40		0.73
Irrigation water use	0.18	0.24	0.29	0.45
Time of working	0.12	0.09	0.20	0.16
Fuel use	0.07	0.04	0.11	0.08

The conclusions arising from these results are the same as previously outlined. With the alternative rotation, yield is still the dominant variable influencing average Gross Margin and RPMI. The impact of yield is even higher under the alternative rotation scenario.

11.1.2.5 Impact of the system benefits of CTF

A scenario considered to be "achievable" under SCTF and CTF management was constructed for the midlands model, with the same values for variables as outlined in Table 11. The results appear in Figures 13 and 14 for Gross Margin and RPMI respectively.

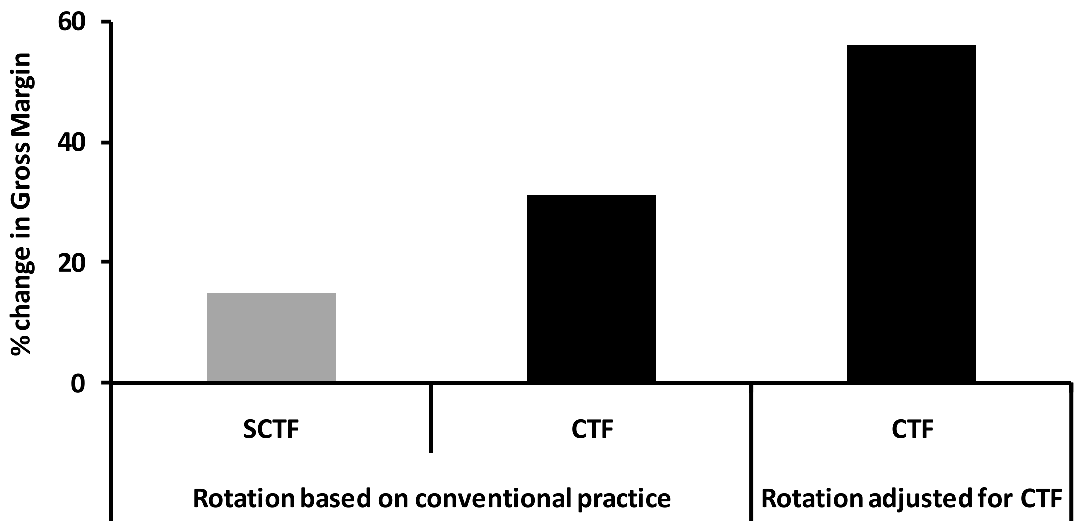

Figure 13. The response of Gross Margin to an "achievable" scenario for SCTF and CTF systems, compared to conventional system.

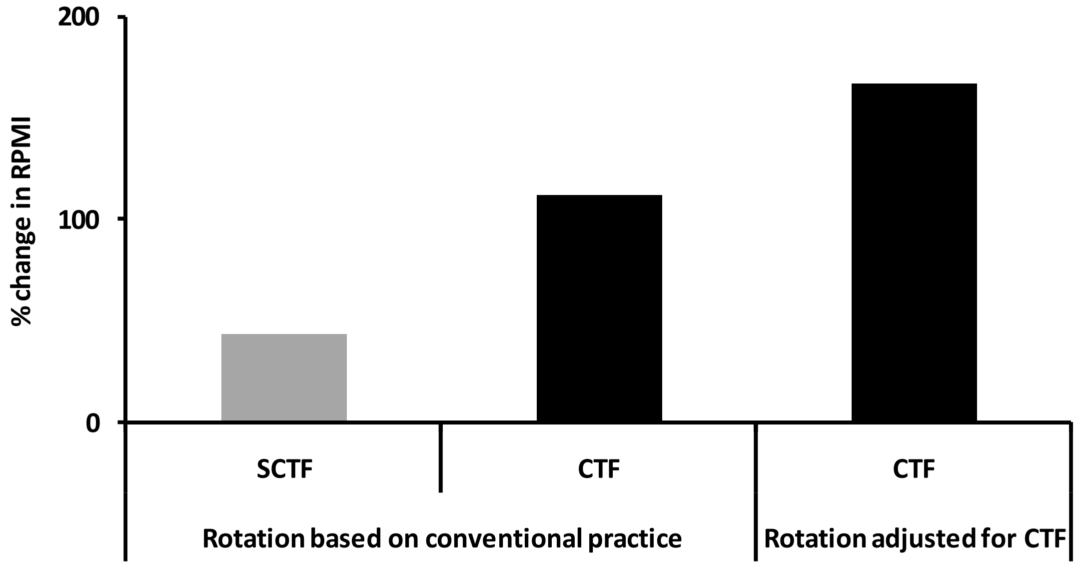

Figure 14. The response of RPMI to an "achievable" scenario for CTF and SCTF systems, compared to conventional system.

Tables 23 and 24 summarise the system impact of CTF on Gross Margin and RPMI, with the influences of rotation separated and the "achievable" scenario displayed in separate columns.

Table 23. % Gross Margin changes (compared to conventional) arising due to rotational and "achievable" option differences

	no change to variables		**"achievable option"**	
Rotation	**SCTF**	**CTF**	**SCTF**	**CTF**
Same for all systems	2	9	15	31
Adjusted for CTF	2	27	15	56

Table 24. % RPMI changes (compared to conventional) arising due to rotational and "achievable" option differences

	no change to variables		**"achievable option"**	
Rotation	**SCTF**	**CTF**	**SCTF**	**CTF**
Same for all systems	19	63	43	112
Adjusted for CTF	19	102	43	167

11.1.2.6 Individual crop Gross Margins, "achievable" scenario

Figure 15 and Table 25 show the Gross Margins for all crops included in the midlands model, not just those included in the rotation used for the analysis above. The graph is structured to show the conventional Gross Margin, and then the additional increase associated with SCTF and CTF systems.

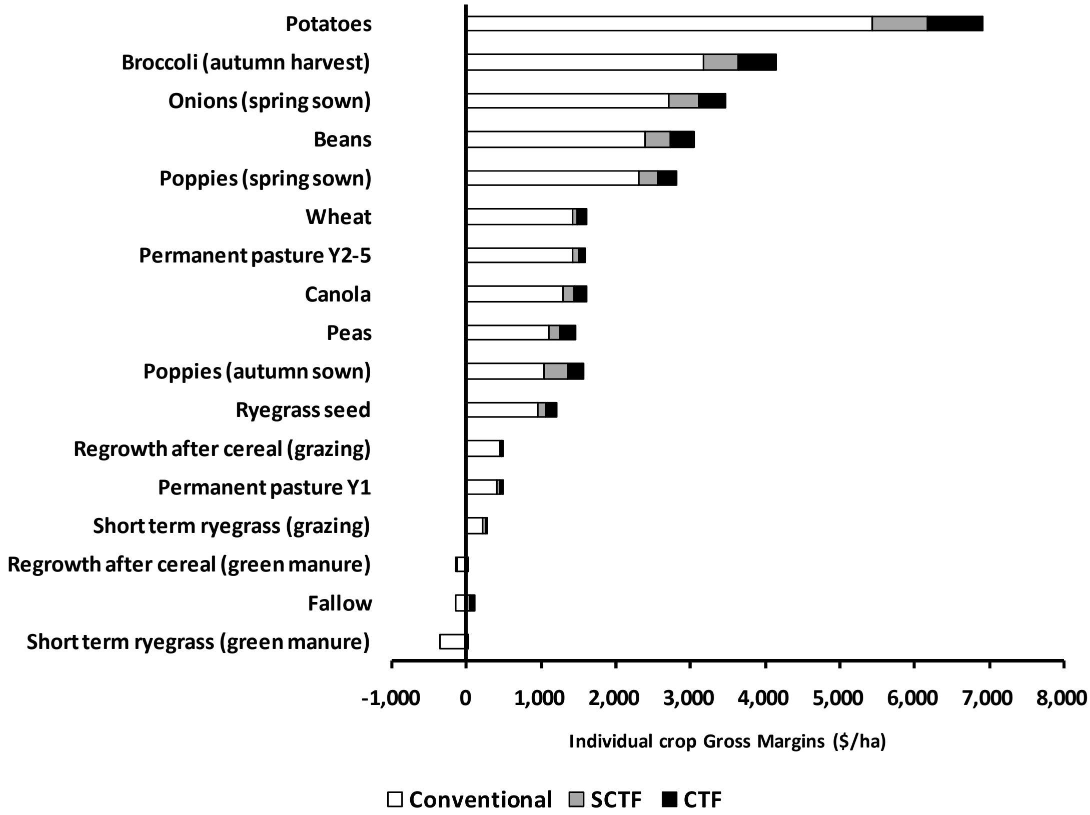

Figure 15. Gross Margins for all crops in the model for the "achievable" option, showing the Gross Margin for the conventional system, and the added benefit arising from SCTF and CTF, midlands model.

Table 25. Gross Margin data ($/ha) for all crops in the model for the "achievable" scenario for the midlands rotation.

Crop	Conventional	SCTF	CTF
Potatoes	5,440	6,160	6,920
Broccoli (autumn harvest)	3,180	3,640	4,140
Onions (spring sown)	2,700	3,100	3,470
Beans	2,390	2,720	3,050
Poppies (spring sown)	2,300	2,560	2,820
Wheat	1,420	1,490	1,610
Permanent pasture Y2-5	1,410	1,500	1,600
Canola	1,280	1,430	1,610
Peas	1,100	1,260	1,460
Poppies (autumn sown)	1,050	1,360	1,570
Ryegrass seed	950	1,050	1,200
Regrowth after cereal (grazing)	440	470	490
Permanent pasture Y1	390	440	480
Short term ryegrass (grazing)	210	250	290
Regrowth after cereal (green manure)	-120	-120	-120
Fallow	-150	-100	-50
Short term ryegrass (green manure)	-350	-340	-330