Controlled traffic for vegetable production: challenges, benefits and opportunities

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Declaration of Originality

The publications presented for the degree are the original works of the candidate, written in conjunction with others. The candidate was the senior author on six of the eight papers included in the thesis, and a significant contributor to the remaining two. The estimated percentage contribution of the candidate and co-authors is shown in the list of publications submitted for the degree under the 'Statement of Co-Authorship' section of the thesis.

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Signed:

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Abstract

Soil degradation is an issue of global concern, given current projections of the need to increase food production, on diminishing soil and water resources, for an expanding population. Compaction is a key component of soil degradation; a key driver of compaction is mechanised agriculture. Early steam technology featured machines that were heavy for the power they delivered. Significant reductions in machine weight came with the introduction of the internal combustion engine in the late 19th century. That was the last time there was a marked decrease in machine weight. Farm machinery has been increasing in size, power and weight ever since, leading to significant increases in soil loading in the past few decades.

The attraction of larger machinery is labour productivity and efficiency. Its major disadvantage is increased severity and depth of soil compaction, leading to a range of issues reflective of reduced soil function: reduced infiltration, aeration, soil biology, soil water storage, drainage, root growth and crop yield, and increased runoff, soil-borne disease pressure and nitrous oxide emissions.

Tillage has been used to remediate the impacts of soil compaction for the entire history of mechanised agriculture. This has traditionally been through the use of mechanical implements, although interest is increasing in the role of plant roots (i.e. biological tillage) to relieve compaction and improve soil function.

As technology has improved, more attention has been given to traction and load support systems that reduce the soil impacts of machine loads. This approach has seen the evolution of rubber tracks, and pneumatic radial and hi-flex low ground pressure tyres. Despite these advances, tyre loads have increased to such an extent that it is difficult to reduce soil stresses below the limits that impact soil function and crop performance. Controlled Traffic Farming (CTF) presents an alternative approach to the management of soil compaction. It is an approach that not only avoids the negative consequences of traffic-induced soil compaction on plant growth and production, but also make use of the positive aspects of compaction to improve traction and trafficability.

The characteristics that define CTF are:

1. All machinery has the same or modular working and track gauge width allowing establishment of permanent traffic lanes.

2. All machinery is capable of precise guidance along the permanent traffic lanes.

3. Farm, paddock and permanent traffic lane layout is arranged to optimise drainage and logistics.

Ideally, all three of these principles would be in place, although because controlled traffic is often retro-fitted to existing farms, layout is often compromised. The first two points above are of prime importance regarding soil compaction management. Ideally, all wheel tracks for all machinery would be coincident, resulting in the minimum possible area of wheel tracks. There are many situations in which this is difficult to achieve, making compromise inevitable with existing mechanisation systems.

The benefits of controlled traffic are numerous, and regardless of the industry sector considered, extend to the entire cropping system. Benefits include:

> improved soil structure, biology, infiltration, soil aeration, soil water storage, internal drainage, water and fertiliser use efficiency, crop growth, yield, timeliness, root crop harvest and economics

and

> reduced runoff, erosion, soil borne diseases, tillage energy use, GHG emissions, number of tillage operations, tillage equipment inventory, tractor size, capital and operating costs and operating hours.

Implementation of a controlled traffic system is not without its challenges. Barriers to adoption may include:

> machinery modification costs, erosion and rutting of compacted traffic lanes, machine tracking on compacted wheel tracks, reduced field efficiency due to traffic constraints, loss of cropped area if wheel tracks are left bare and reduced yield from wheel tracks if they are cropped.

CTF has had its biggest commercial impact in the Australian grain industry over the past 25 years. Uptake in other industries, including the vegetable industry, has been much slower, with many of the reasons related to machinery.

There are a number of soil management reasons as to why the vegetable industry would benefit from the introduction of controlled traffic. Characteristics of the vegetable industry that create particular challenges for sustainable soil management include:

- constantly moist-to-wet soils, particularly in temperate climates, as winter dominant rainfall and summer irrigation frequently create conditions conducive to soil compaction
- high input/high value per hectare (compared to rain-fed grain production) such that in-season productivity is usually prioritised over long-term sustainability
- high levels of soil disturbance in some harvest operations (e.g. for roots and tubers)
- high materials handling rates at harvest
- high traffic intensity in terms of load and tracked area
- limited flexibility to delay harvest in order to wait for improved soil conditions
- intensive tillage
- low levels of soil cover for protection of the soil resource
- diverse crop rotations requiring a range of machinery designs and functionality.

In relation to this last point, the industry is constrained in its adoption of controlled traffic due to the complexities of achieving dimensional integration across a range of machines (particularly harvesters) used in the production of a variety of crops with differing characteristics, such as:

- growth habit (e.g. fruiting *cf* root and tuber crops)
- spatial arrangement (e.g. rows *cf* broadacre)

- harvest processing requirement (e.g. separation of harvested parts from the soil *cf* removal of harvested parts from the plant).

This thesis brings together a body of research related to controlled traffic as it applies to the Tasmanian vegetable industry, although the findings would be relevant to many vegetable production areas that feature mixed crop rotations, mechanised harvest and undulating topography, either singly or in combination. It begins with an analysis of the diversity of machinery used and the impacts posed by the undulating topography of the main vegetable production regions. These circumstances are in significant contrast to the limited equipment suite and flat to mildly sloping topography that are features of the Australian grain industry, which has experienced successful adoption of CTF. The analysis showed that integration of machinery is a very significant challenge. Few machines used in the industry are suited to modification to enable CTF operation. Seasonal CTF provides a starting place for adoption. Mapping analysis showed that steeply undulating topography may not necessarily present significant challenges. Many fields already feature working layouts that are consistent with slope direction, which has advantages for both machinery operation and soil conservation measures under a controlled traffic system.

The thesis then moves on to the response of soil to the implementation of controlled traffic. Field trials of controlled traffic in different production environments in Tasmania demonstrated improvements in soil physical properties, and a reduction in tillage operations (20 - 60%), compared to conventional production systems. Some measures of soil properties varied over the course of the research due to the limitations of machinery used, leading to compromises in the integrity of the controlled traffic system. Accurate machinery tracking in undulating topography proved challenging. An investigation of the impact of controlled traffic on the soil arthropod assemblage was undertaken. Spring sampling showed improvements in arthropod abundance ($p<0.01$) and richness ($p<0.1$), and collembolan abundance ($p<0.01$) under controlled traffic. Arthropod abundance was also greater in winter ($p<0.1$). While improvements in arthropod abundance and richness do not necessarily create an advantage for vegetable production, the higher populations and diversity suggest improvements in the soil environment which imply benefits for soil biology in general.

The potential economic benefit of controlled traffic systems is an important consideration. Without fully integrated controlled traffic systems to serve as economic case studies, modelling was used to determine the difference in returns of three different vegetable farming systems. Data from conventionally operated farms and controlled traffic research helped inform the modelling. With many uncertainties to be resolved regarding vegetable industry conversion to controlled traffic, a conservative approach was taken to estimate the changes likely to occur due to adoption. Modelling indicated median increases in average returns of up to 29%.

Economic modelling was based on the assumption that existing machinery could be modified to enable implementation of controlled traffic, an approach that remains unproven. A possible solution to the constraint of machinery incompatibility is the gantry or wide span (WS) tractor, which would provide a mechanisation platform suited to the adaptation and mounting of a wide range of implements and harvest technologies. Wide span tractors are not commercially available, although a Danish prototype used in field trials on a commercial farm in 2014 was used as the basis of the modelling. Once again, conservative estimates of costs and returns were applied to case study farm scenarios. Median increases in average returns of up to 59% were indicated. Sensitivity analysis showed that the most important cost factors were machinery capital and potential reductions in harvest efficiency, while predicted improvements in crop yield offered the most significant benefits.

Wide span tractors offer a ‘controlled traffic friendly’ approach to mechanisation for the vegetable industry. A range of conventional implements could be mounted within the span of a WS and there is scope to modify existing harvest technology to fit the system. While there would be challenges to such a change, they may be no more difficult than achieving change within current machinery inventories. The wide, non-trafficked crop beds achievable with a WS may permit altered crop spatial arrangements and potentially provide up to 20% greater yield per hectare in some crops through reduction of wheel track area leading to increased plant population per hectare. There is also scope to integrate conventional tractors with WS harvesters to provide a staged change process.

The papers contained in this thesis repeatedly note the challenges presented by the lack of dimensional integration in vegetable production machinery. Integrated ‘swarms’ of light-weight autonomous machinery have been suggested as an alternative means of reducing traffic compaction. Modelling of grain and potato harvester machinery parameters was used to determine specifications of possible light-weight harvesters for use in soil compaction modelling. This showed that, to limit soil bulk density to 1.4 Mg m^{-3} for the soil conditions used in modelling, the maximum gross vehicle mass (GVM) of a grain harvester was 6 Mg. This would require a fleet of 6 - 9 harvesters (~50 kW), with access to unloading facilities every 2.5 - 3 minutes, to replace a single Class 9 (>300 kW) harvester. No light-weight option could be found that would avoid compaction of the highly disturbed soil resulting from root and tuber crop harvest. The use of medium-capacity autonomous machines (e.g. ~10 - 20 Mg GVM for the grain harvester scenario) within a controlled traffic system may be a better solution for both soil compaction and operational logistics than light-weight swarm technology.

Despite the many benefits of controlled traffic, the vegetable industry, particularly in situations featuring diverse rotations of crops, remains constrained by machinery designs that are incompatible with the basic principles of the system – i.e. dimensional integration of track gauge and working width. The industry needs an alternative approach to mechanisation to achieve a more sustainable production system based on protecting soil from the negative impacts of excessive traffic and tillage. The Wide Span, proven under steam power in the 1850s, offers such an approach using a standard tool carrier to which current implements and harvest technologies could be attached following relatively simple changes to design.

Impact statement

This thesis contains publications that date from 2013 to the present comprised of seven peer-reviewed and published research papers and one peer-reviewed and published conference paper. Searches of Web of Science and Scopus based on the terms ‘controlled traffic’, ‘permanent raised beds’ and ‘vegetable’ reveal 16 references dating back to 1985 that describe specific research related to vegetable production systems. A further eight note the relevance of controlled traffic to vegetable production. The candidate has co-authored eight (six as lead author) of the articles referenced, with a total citation record of 52 as reported in Table C-1 (Appendix C).

Acknowledgements

Undertaking my PhD was never a major feature on the landscape of my career. After all, in the late 1980s my then manager had to cajole me into doing my Masters, which I completed in 1992, 14 years after finishing my undergraduate studies. Now, 28 years later (I see a mathematical progression starting here) I am submitting my PhD. When I arrived in Tasmania in 1991 to undertake RD&E in the vegetable industry, fresh from five years of irrigated grains-related controlled traffic research 2400 km further north, I knew nothing about the industry, although one thing was immediately apparent (to me) – if ever there was an industry in need of a soil compaction management solution, it was the vegetable industry. While progressing a range of projects covering various aspects of the vegetable industry, I constantly looked for opportunities to pursue the idea of controlled traffic in vegetable production. After many years, my efforts, with the support of others, led to a series of projects that culminated in the papers contained in this thesis. It was a journey that reinforced to me the importance of how we manage our soil, and that we need to get much better at it.

The collection of papers that had been written as a result of those projects constituted a body of work that is unusual in the controlled traffic arena, in that they all focused on the vegetable industry, which is far more complex than the grain industry, the natural 'home' of controlled traffic. I felt this collection of publications somehow needed to be brought together as a whole, although undertaking a PhD as part of that process was not something that naturally came to mind. The PhD pathway came about very much by accident when I stumbled across a University of Tasmania policy on 'PhD by Prior Publication'. Following advice from others more versed in these matters, I decided to give it a go – after first giving careful consideration as to how it would impact on my after-hours mind-clearing hobbies of playing music and bushwalking.

Even though I had the challenge of fitting it in alongside full-time (and more) work, the idea of a PhD by Prior Publication sounds enticing – after all, hasn't all the hard work been done? I was told I needed to bring my papers together in a 'cohesive story, book-ended by an Introduction and Conclusion'. All very well, except the projects I had done, and their subsequent papers, appeared to be scattered randomly over the vast landscape of topics that can be pursued within the scope of 'controlled traffic farming', with many gaps in between. Nevertheless, I have given it a go, and am now able to present the results of my version of tying together a number of different threads under the broad banner of 'controlled traffic'.

There are many people to thank for their support and contributions during the journey of producing this thesis. Without the papers presented herein, there would be no PhD by Prior Publication, so firstly I acknowledge all my co-authors, some of whom were also supervisors:

- Mr. Peter Aird, Serve-Ag Pty Ltd, Devonport, Tasmania. Pete was the first 'kindred soul' I found in Tasmania who, despite the many challenges in the vegetable industry, understood the potential of controlled traffic, and has been a valuable contributor to, and supporter of, much of the RD&E work undertaken. He has also been instrumental in some adoption successes in the industry.

- Mr. Tim Neale, CTF Solutions (now Data Farming), Toowoomba, Queensland. Tim has a wealth of knowledge and experience in controlled traffic layout planning (amongst many other topics) and his input to an early project and paper was invaluable.

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- Dr. Ross Corkrey, Tasmanian Institute of Agriculture, University of Tasmania, Hobart, Tasmania. Ross is my 'go to' person for statistics. He has guided me through many data wildernesses.

- Dr. Denis Rodgers, Environmental Futures Research Institute, Griffith University (currently Rosewood Geotechnical, Rosewood, Queensland). Until we embarked on the soil biology work reported herein, I had never met anyone whose first and last (professional) love is soil arthropods.

- Mr. John Maynard, Macquarie Franklin, Devonport, Tasmania (retired). John's knowledge of Tasmanian agri-business made him an obvious collaborator on the initial economics work reported in this thesis, and his work on the modelling set the foundation for both economics papers.

- Dr. Hans Henrik Pedersen, Department of Engineering, Aarhus University, Denmark. I first met Hans Henrik in 2007 at a CTF workshop in The Netherlands and was fortunate to host him in Tasmania for five months over 2014-15 while he worked on his PhD about wide-span controlled traffic. His time in Tasmania led to a lasting connection between our families and two of the papers included in this thesis.

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- Dr. Tim Chamen, CTF Europe, Maulden, UK. I first met Tim at a conference in Sweden in 1992 and our paths have crossed on a number of professional and social occasions since, in both the northern and southern antipodes. His passion for wide-span technology as the basis of controlled traffic has been a significant influence on my thinking about future directions for vegetable CTF. He also knows a bit about embarking on a PhD later in life.

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- Dr. Mark Boersma, Tasmanian Institute of Agriculture, University of Tasmania, Burnie, Tasmania. Mark has been a valuable contributor and rigorous reviewer whose input as supervisor and co-author has always been welcomed – after I had overcome my initial reaction and had time to think about it.

I thank the Tasmanian Institute of Agriculture (TIA), University of Tasmania, for an on-going period of employment that spans the time when the project work and subsequent paper writing were done and being supportive of my decision to embark on my PhD. The work reported in this thesis was largely done as part of externally funded projects, support for which is appreciated and acknowledged in each publication as appropriate. A large number of people in the vegetable industry, too many to name here, also deserve acknowledgement, including farmers, advisors, contractors, consultants, machinery manufacturers and others who have assisted to varying degrees on projects, and often entertained discussions on what, at times, must have seemed crazy ideas.

Thanks also to Dr. Karen Christie who had nothing to do with my thesis other than she preceded me through the PhD by Prior Publication administrative process, which is relatively uncommon and hence prone to a few bumps in the road. Your smoothing of the way and advice on various matters have been much appreciated.

Although it is many years ago now, I am grateful for the opportunity to have grown up on a mixed farm which founded my interest in agriculture. My father was considered progressive, particularly in terms of soil conservation and management, although I look back now and wonder how much better our soils might have performed with the understanding we now have of the negative impacts of traffic and tillage. While approaches such as controlled traffic were ‘pie in the sky’ in their era, I have no doubt my parents would understand the importance of what is now possible.

Thank you to my children, Lisa and Ro. Undertaking my PhD later in life, after both had left home for their own studies, meant I didn’t have to juggle evening and weekend ‘kid time’ – although they do like a long chat on the phone, for which I am grateful, even if sometimes I have had to pull myself back to the keyboard when I would have been just as happy to keep chatting. They have been very supportive – I suspect mainly for the prospect that one day they might see their father wear a floppy hat at graduation.

Agriculture is not in their blood, but I appreciate their understanding of what I do and why I do it. At the very least, they have grown up with a controlled traffic, zero-till veggie patch that has permanent walkways and constant plant and/or residue cover.

Finally, thanks to my wife, Trish. We are undoubtedly well suited. As a dedicated and passionate maths/science teacher, she spends many nights improving her already impressive teaching program, so she had few concerns about me retreating to the front office to work on my writing. Thanks for your patience – soon it will be time for more music of an evening, more time in the bush and more activities and adventures together.

Statement pertaining to this thesis

This thesis is based on published works from research projects conducted by the PhD candidate and is presented in accordance with requirements set by the University of Tasmania for PhD by Prior Publication. The publishers of the papers comprising Chapters 3 to 6 hold the copyright for that content, and access to the material should be sought from the respective journals. The remaining non-published content of the thesis may be made available for loan and limited copying and communication in accordance with the Copyright Act 1968.

The thesis includes the following elements:

- statements of co-authorship
- an introduction outlining a common theme that links the individual publications
- a critical review of literature relating to controlled traffic for crop production, including aspects related to machinery, soil, crops and economics
- eight prior-published peer-reviewed publications assembled in to four chapters (Chapters 3 to 6), each containing two papers on a related topic
- a short introduction preceding, and a focused discussion following, each of Chapters 3 to 6
- a concluding summary and discussion chapter
- a list of all references cited in the thesis
- a supplementary list of references relevant to the yield impacts of soil compaction as discussed in the literature review
- a list of references specific to controlled traffic research in the vegetable industry
- the number of citations for the published papers, and a list of other publications, book chapters and conference proceedings credited to the candidate that have contributed to the literature and discussion regarding controlled traffic in vegetable production in Australia and overseas.

Statement of Co-authorship

The following people and institutions contributed to the publication of the work undertaken and presented as part of this thesis:

- **Candidate** - Mr John McPhee, Tasmanian Institute of Agriculture, Burnie, University of Tasmania
- **Author 1** - Mr. Peter Aird, Serve-Ag Pty Ltd, Devonport, Tasmania
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- **Author 13** (and Supervisor) - Dr. Mark Boersma, Tasmanian Institute of Agriculture, University of Tasmania, Burnie, Tasmania

This thesis contains seven peer-reviewed papers that were published prior to the completion of the candidature, and one manuscript awaiting editorial decision following completion of peer-review and revision. These are listed below, with authorship, title of publication, journal details and contribution by the candidate and co-authors.

Publication 1: Located in Chapter 3

McPhee, JE and Aird, P, (2013) 'Controlled traffic for vegetable production: Part 1. Machinery challenges and options in a diversified vegetable industry', *Biosystems Engineering*, **116** (2) 144-154

- Candidate contributed 70%: developed the concept, conducted all desktop and field work, analysed the data and wrote the manuscript

- Author 1 contributed 30%: assisted with the concept and field work and revised the manuscript

Publication 2: Located in Chapter 3

McPhee, JE, Neale, T and Aird, P, (2013) 'Controlled traffic for vegetable production: Part 2. Layout considerations in a complex topography', *Biosystems Engineering*, **116** (2) 171-178

- Candidate contributed 60%: developed the concept, assisted with mapping and field work and wrote the manuscript

- Author 1 contributed 15%: assisted with the concept, assisted with field work and revised the manuscript

- Author 2 contributed 25%: conducted mapping work and revised the manuscript

Publication 3: Located in Chapter 4

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

- Candidate contributed 55%: developed the concept, conducted most of the experimental work, interpreted data analysis and wrote most of the manuscript

- Author 1 contributed 15%: assisted with the concept, field work and revised the manuscript

- Author 3 contributed 10%: assisted with writing and revision of the manuscript

- Author 4 contributed 20%: conducted most of the data analysis, assisted with data interpretation and revised the manuscript

Publication 4: Located in Chapter 4

Rodgers, D, **McPhee, J**, Aird, P and Corkrey, R, (2018) 'Soil arthropod responses to controlled traffic in vegetable production', *Soil and Tillage Research*, **180**, 154-163

- Candidate contributed 40%: assisted with development of the concept, analysis of the data and writing of the manuscript

- Author 1 contributed 5%: revised the manuscript

- Author 4 contributed 20%: conducted most of the data analysis, assisted with data interpretation and revised the manuscript

- Author 5 contributed 35%: developed the concept, conducted the field work and assisted with analysis of the data and writing of the manuscript

Publication 5: Located in Chapter 5

McPhee, JE, Maynard, JR, Aird, PL, Pedersen, HH and Tullberg, JN, (2016) 'Economic modelling of controlled traffic for vegetable production', *Australian Farm Business Management Journal*, **13**, 1-17

- Candidate contributed 50%: developed the concept, assisted with data collection, model development and interpretation, and wrote the manuscript
- Author 1 contributed 10%: assisted with data collection and revised the manuscript
- Author 6 contributed 20%: developed the model
- Author 7 contributed 10%: assisted with modelling and revised the manuscript
- Author 8 contributed 10%: assisted with modelling and revised the manuscript

Publication 6: Located in Chapter 5

McPhee, J and Pedersen, HH, (2017) 'Economic modelling of controlled traffic for vegetable production based on the use of wide span tractors', *Australian Farm Business Management Journal*, **14**, 71-88. ISSN 1449-7875

- Candidate contributed 60%: developed the concept, assisted with data collection, model development and interpretation, and wrote the manuscript
- Author 7 contributed 40%: assisted with model development, interpretation, and revised the manuscript

Publication 7: Located in Chapter 6

Pedersen, HH, Oudshoorn, FW, **McPhee, JE** and Chamen, WCT, 'Wide span – re-mechanising vegetable production', (2016) *Acta Horticulturae*, 2016.1130.83. XXIX IHC - Proc. Int. Symposia on the Physiology of Perennial Fruit Crops and Production Systems and Mechanisation, Precision Horticulture and Robotics, pp. 551-557. ISSN 0567-7572

- Candidate contributed 40%: co-developed the concept and co-wrote the manuscript
- Author 7 contributed 40%: co-developed the concept and co-wrote the manuscript
- Author 9 contributed 10%: revised the manuscript
- Author 10 contributed 10%: revised the manuscript

Publication 8: Located in Chapter 6

McPhee, JE, Antille, DL, Tullberg, JN, Doyle, RB, Boersma, M, (2020) 'Managing soil compaction –a choice of light-weight autonomous vehicles or controlled traffic?', *Biosystems Engineering,* **195** (227-241).

- Candidate contributed 65%: developed the concept, conducted all field, laboratory and modelling work, analysed the data and wrote the manuscript
- Author 8 contributed 5%: revised the manuscript
- Author 11 contributed 15%: provided data sets, assisted with interpretation of model outputs and revised the manuscript
- Author 12 contributed 5%: revised the manuscript
- Author 13 contributed: 10% revised the manuscript

We, the undersigned, endorse the above stated contribution of work undertaken for each of the published peer-reviewed manuscripts contributing to this thesis:

Mr John McPhee, Candidate Tasmanian Institute of Agriculture, University of Tasmania, Burnie, Tasmania (1 April 2020)	Dr. Richard Doyle, Primary Supervisor, Tasmanian Institute of Agriculture, University of Tasmania, Hobart, Tasmania (12 March 2020)	Prof. Michael Rose, Interim Director, Tasmanian Institute of Agriculture, University of Tasmania, Hobart, Tasmania (2 April 2020)

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CHAPTER 1. INTRODUCTION

1.1 Background

Sustainable development was defined by the World Commission on Environment and Development (a.k.a. Bruntland Commission, UN General Assembly Resolution 42/187, 11 December 1987) as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. Sustainability has been the catch cry of agricultural advances for several decades. This is entirely reasonable, given that agriculture represents the most disruptive intervention of the natural environment, in terms of land and water use, by *Homo sapiens*.

Issues of agricultural sustainability are difficult to escape in the on-going global narrative of pressure on food supplies caused by increasing population, diminishing resources and predicted climate change impacts. Popular media and peer-reviewed literature regularly report the need for increased production, whilst simultaneously reducing unsustainable demands on soil and water resources, most of which are the result of intensification or expansion of production.

Production intensification is one approach, along with reductions in supply chain waste and improved re-distribution of supplies, that can help meet future demands for food, fibre and bio-fuel. Many technological advances in plant breeding, nutrition, irrigation, mechanisation, precision agriculture and controlled environments have driven production intensification in recent decades. The challenge for agriculture is that intensification can't be at the expense of resource sustainability, particularly in relation to soil and fresh water (Bolton & Crute, 2011).

The challenges and impacts of mechanisation are central to the research presented in this thesis. Mechanisation had a profound effect on agriculture in the 20th century. Schueller (2000) noted that 'At the start of the 20th century a U.S. farmer fed about 2½ people. Today, that farmer feeds 97 Americans and 32 living abroad'. Similar increases in productivity have occurred in most developed countries. Mechanisation has been a significant contributor to this astounding increase in production per farmer, with large machinery allowing fewer people to do more work, in a more-timely fashion, over larger areas. However, mechanisation has come at a cost – equipment traffic is the primary contributor to soil compaction in field-based cropping systems (Keller et al., 2019; Wang et al., 2008), and that is a key challenge for sustainability.

Underpinning agricultural sustainability is the capacity of the soil to continue to provide production and ecosystem services whilst subject to intense modification and manipulation in the pursuit of increased productivity. Widespread global soil degradation caused by agriculture, which is due to many factors related to production system management, suggests that current efforts fall short of what is required to ensure sustainable food production from the current soil resource (Hou et al., 2020). Changes to agricultural practices which not only preserve the soil, but also enhance its rehabilitation, are needed to ensure future sustainability. Such changes must consider the impacts of current and future production practices on the soil and the productivity and economics of the farming system (Cooper et al., 2020).

Fortunately, it is possible for field-based production systems to increase productivity and improve soil and water sustainability at the same time. Controlled traffic farming (CTF) is one such approach that achieves these dual benefits. CTF is applicable to all field-based cropping systems, although the challenges of adoption vary considerably between sectors. The greatest commercial adoption of CTF has occurred over the past three decades in the Australian grains industry, where it has proven to be a crop production system with the capacity to restore soil function while also improving system productivity.

1.2 What is controlled traffic?

Controlled traffic is the basis of cropping systems in which all load bearing wheels or tracks of heavy machinery are confined to the smallest possible area of permanent traffic lanes. In an ideal system, all wheel tracks for all machinery would be coincident, resulting in the minimum possible area of wheel tracks. There are many situations in which this is difficult to achieve, making compromise inevitable under existing mechanisation systems.

1.3 What is the purpose of controlled traffic?

In terms of sustainable management of the soil resource, mechanised agriculture faces a significant quandary. It is difficult to express it more logically than in the words of Taylor (1985) '1. Tires need firm, dry soil for optimum traction and flotation; 2. Plants need uncompacted soil with good moisture for optimum growth; 3. Tires operated on soils that are in optimum plant growth condition will change the soil condition to one that is optimum for traction and flotation. Controlled traffic optimises soil conditions for both traffic and crops, even though their requirements are almost exact opposites.' Alternatively, in the succinctness of Tullberg (2006), 'Wheels work better on hard soil, plants grow better in soft soil'.

1.4 Benefits and disadvantages

The benefits of controlled traffic are numerous and extend to the entire cropping system, regardless of the industry sector considered. Benefits reported in peer-reviewed literature and observed in commercial practice include improved soil structure, biology, infiltration, soil aeration, soil water storage, internal drainage, water and fertiliser use efficiency, crop growth, yield, timeliness, root crop harvest and economics (Antille et al., 2019; Dickson et al., 1992; Kingwell & Fuchsbichler, 2011; McGarry, 2003; McHugh et al., 2009; McPhee et al., 2015; McPhee et al., 1995c; Neale & Tullberg, 1996; Powrie & Bloomer, 2010; Rodgers et al., 2018; Vermeulen et al., 2010). Further, benefits of CTF are measured not only in improvements or increases in positive aspects, but also reductions in negative aspects and costs, such as reduced runoff, erosion, soil borne diseases, energy use for tillage, GHG emissions, number of tillage operations, tillage equipment inventory, tractor size, capital and operating cost and operating hours (McPhee et al., 2015; McPhee et al., 1995b; Neilsen, 2008; Stirling, 2008; Tullberg et al., 2018; Tullberg, 2000).

Despite the many advantages attributed to controlled traffic, adoption of the principles, and the system overall, is not without its challenges. Barriers to adoption vary between industries and individual grower circumstances, and include machinery modification costs, erosion and rutting of compacted traffic lanes, machine tracking on compacted wheel tracks, impacts on field efficiency due to traffic constraints, loss of cropped area if wheel tracks are left bare and reduced yield from wheel tracks if they are cropped (Bochtis et al., 2010; Bochtis et al., 2009; Hagny, 2005; Isbister et al., 2013; McPhee et al., 2015; Mitchell et al., 2019).

1.5 History

Although the first commercial adoption of controlled traffic of any mechanised scale occurred in the Central Queensland grain industry in the mid-1990s (Tullberg et al., 2007), the concept is hardly new. It is likely that the principles of controlled traffic were employed for thousands of years by those who prepared seedbeds for cropping, as they would have seen little point in trampling down soil they had just dug. The first known published reference to the technique, although not named as such, was in a paper presented to the Society of Arts, London (Halkett, 1858). At a time when agricultural mechanisation was centred on steam traction engines, Halkett devised a wide span gantry system (a specific approach to controlled traffic), which travelled on rails in the field, leaving a 9 m span of untrafficked soil for the growth of crops.

Interest in the concept of controlled traffic seems to have then disappeared from published records until the late 1960s, when it reappeared primarily as a research tool providing the means to study plant growth free of the effects of soil compaction (Cooper et al., 1969; Taylor & Bruce, 1968). Since that time, there has been a steady increase in the number of peer-reviewed and conference papers published. A basic search of all databases through Web of Science shows the following decadal trend of publications making specific mention of the terms 'controlled traffic' and 'permanent raised beds'[1] in the title, paired with the topic of 'agriculture' – 1980-89 (7), 1990-99 (7), 2000-09 (17) and 2010-2019 (53). If the search is widened to the less restrictive option of 'controlled traffic' and 'permanent raised beds' as topics, the results are – 1980-89 (17), 1990-99 (29), 2000-09 (67) and 2010-2019 (98). These searches may not necessarily reflect all publications on the topic, but the increased interest over the past two decades is evident.

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[1] While the term 'controlled traffic' is the most widely used descriptor for the system of traffic management discussed in this thesis, other terminology is also used. 'Permanent raised beds' describes production systems in which the crop growth zone is deliberately raised above the level of the wheel tracks for reasons that may relate to improved surface drainage, facilitation of furrow irrigation, provision of a greater depth of soil for root growth or easier harvest operations. The furrows between the raised beds are also the wheel tracks, although not all furrows will necessarily be used as such. 'Tramlines' is another term sometimes used in relation to controlled traffic, although it is more widely used in the UK and Europe to describe wheel tracks that are left unsown (in cereal crops) for the use of in-season spray and fertiliser application operations. The number of controlled traffic related papers in which the term 'tramlines' is used is quite small, so these were excluded from the details given here.

The grains industry has led the commercial adoption of CTF, although uptake of the practice varies between industry sectors and countries (Chamen, 2015; Tullberg et al., 2007). While research has provided much of the evidence of the benefits of controlled traffic, farmers have provided the lead in adjusting machinery to make the system functional at the farm level. With a few exceptions, the manufacturing industry has been very slow to respond.

1.6 The vegetable industry

Soil management and sustainability is challenging in the vegetable production environment. Some characteristics of the vegetable industry that make it so are:

- high traffic intensity in terms of load and tracked area
- intensive tillage
- high levels of soil disturbance in some (e.g. root and tuber) harvest operations
- high materials handling rates at harvest
- low levels of soil cover for protection of the soil resource
- constantly moist-to-wet soils, particularly in temperate climates, as winter dominant rainfall and summer irrigation frequently create conditions conducive to soil compaction
- high input/high value per hectare (compared to rain-fed grain production) such that in-season productivity is usually prioritised over long-term sustainability
- limited flexibility to delay harvest in order to wait for improved soil conditions
- diverse crop rotations requiring a range of machinery designs and functionality.

The vegetable industry faces many challenges in the uptake of controlled traffic, with diversity of machine designs, particularly harvesters, being a key factor. Hand-harvested crops present fewer challenges, and production systems based on beds lend themselves to controlled traffic (Rogers et al., 2001; Vedie et al., 2008), although many are not managed as such. Machine harvested crops present greater difficulties due to the differing requirements, and hence differing designs, of vegetable harvesters (McPhee et al., 2018; McPhee & Aird, 2013).

Vegetable production in Tasmania occurs largely in a mixed farming context, in which growers may produce crops as diverse as potatoes, onions, carrots, peas, beans, broccoli, cauliflower, pyrethrum, poppies, cereals and other grains, and fodder for cutting and grazing, with cropping enterprises sometimes integrated with livestock. Most growers rely on contractors for operations that require high capital cost machinery, such as harvest, and increasingly for other machinery operations. Both machinery ownership and diversity of design present particular challenges to the adoption of controlled traffic in the vegetable industry (McPhee et al., 2018; McPhee & Aird, 2013). This issue is particularly relevant, although not unique, to the Tasmanian situation.

Soil degradation is a long running issue in the vegetable industry, partly as a function of the topography (particularly in Tasmania, but also other regions) and its influence on erosion (Basher & Ross, 2002; Cotching, et al., 2002; Sparrow et al., 1999), and partly because of agricultural management practices including machinery traffic and tillage operations (Bridge & Bell, 1994; Cotching et al., 2001; Cotching et al., 2002). Heavy machinery, high traffic intensity and moist soil at many times during the cropping season, particularly at harvest, all contribute to soil compaction and degradation. Controlled traffic offers an alternative to restore and maintain soil quality and productivity if the challenges of machinery design and integration can be overcome.

1.7 Research rationale and thesis structure

The rationale for the research reported in this thesis was to explore a number of aspects of controlled traffic as they relate to vegetable production, with particular reference to the Tasmanian vegetable industry. Embodied in this exploration is an assessment of the challenges and benefits of controlled traffic for vegetable production, and the integration of what is currently known from this and other research to describe a system capable of ensuring more sustainable vegetable production into the future. Two aspects of sustainability are investigated in this thesis, being sustainability of the soil resource and enterprise economics. Soil sustainability refers to the capacity of soil to meet the needs of current production requirements without compromising future production. Economic sustainability refers to the capacity of the enterprise to generate sufficient (and preferably improved) returns to ensure longevity.

An over-arching hypothesis was developed, being:

- Controlled traffic provides the basis for improving the soil sustainability and economics of vegetable production but is dependent on mechanisation platforms that allow dimensional integration over all field operations.

A number of sub-hypotheses were also developed, namely:

- Variations in design of machinery used in the vegetable industry are a significant barrier to uptake of controlled traffic.

- Complex topographies present barriers to adoption of controlled traffic for vegetable production.

- Controlled traffic leads to improved soil physical and biological conditions.

- Controlled traffic improves the economics of vegetable production at the farm level through a range of influences, including reduced tillage requirements, improved timeliness, lower costs and improved yield.

- A paradigm change in mechanisation is required to achieve a universal solution for the successful implementation of controlled traffic in vegetable production.

In the context of controlled traffic research generally, peer-reviewed literature related to controlled traffic in vegetable production is sparse. A rudimentary literature search covering the past 45 years reveals <100 published papers with the words 'controlled traffic' or 'permanent raised beds' (in relation to agriculture) in the title, and <220 papers that cover those topics within their contents. When it comes to vegetable production specifically, these figures reduce dramatically. A total of 23 papers are revealed, 16 describing specific aspects of controlled traffic in vegetable production, and seven the mention its relevance within the topic scope of the paper (Appendix B).

The work which comprises the body of this thesis was done to determine the applicability and benefits of controlled traffic for vegetable production in the context of the industry characteristics and hypotheses outlined above and with specific focus on:

- Challenges – machinery and layout
- Benefits – soil and economics
- Opportunities – changes that remove the constraints and capture the benefits through the synergistic combination of all elements of the system

The thesis structure, and the research questions addressed in the various chapters, are outlined below.

Chapter 1. Introduction

Chapter 1 provides a background to soil sustainability challenges in cropping industries, the role that controlled traffic can play in improving crop production sustainability and a description of some of the characteristics of the Tasmanian vegetable industry.

Chapter 2. Literature review

Chapter 2 is a review of literature covering many aspects of controlled traffic in crop production. It necessarily draws on information from a range of industries, particularly because the literature specifically related to the application of controlled traffic in vegetable production is sparse. Because this thesis has been prepared for the attainment of a PhD by Prior Publication, the literature review also draws on the research that is reported in Chapters 3 to 6, which helps to position these sources alongside the global literature.

Chapter 3. Machinery integration and layout considerations in vegetable cropping systems

Chapter 3 is comprised of two previously published papers that highlight key challenges to the adoption of controlled traffic in the vegetable industry. As is the case for most mechanised vegetable production, the Tasmanian industry uses a diverse range of equipment, none of which has been designed with the concept of dimensional integration in mind. This presents challenges for the integration of machinery in a controlled traffic system. The first of the two papers is the only known published paper that systematically analyses the mechanisation constraints at an industry level. The second paper assesses the degree to which steeply undulating topography, a feature of the Tasmanian vegetable industry landscape, may impact the design of optimum field layouts for controlled traffic.

The research questions addressed in Chapter 3 are:

- How serious are the constraints to the adoption of controlled traffic in mechanised vegetable production, with particular reference to the Tasmanian industry?

- Do the constraints apply only to mechanisation, or are there other factors?

Chapter 4. Impact of controlled traffic on soil properties and management in a vegetable production system

Chapter 4 is comprised of two previously published papers that report on some of the soil management benefits that arise through the adoption of controlled traffic for vegetable production. Based on replicated and demonstration field work at three sites, the papers report on matters such as changes in soil physical properties and soil biology, as well changes in the requirements for tillage subsequent to the isolation of wheel traffic to permanent traffic lanes.

The research question addressed in Chapter 4 is:

- Could the adoption of controlled traffic in vegetable production systems that rely on tillage for seedbed preparation and residue management provide similar soil health and productivity benefits to those obtained in controlled traffic, zero-till grain production systems?

Chapter 5. Economic modelling of controlled traffic in vegetable production

Chapter 5 is comprised of two previously published papers that detail modelling undertaken to assess the potential economic benefits of controlled traffic adoption in the vegetable industry. Since the adoption of controlled traffic in vegetable production is currently constrained by machinery design factors, rigorous case study analysis is not an option for investigating the economics of adoption. Whilst the assumptions used in modelling are always open to challenge, the use of conservative estimates and risk and sensitivity analyses can provide a degree of confidence in the results and help to highlight areas of key importance when considering an adoption strategy.

The research questions addressed in Chapter 5 are:

- If it was possible to modify existing equipment to suit controlled traffic in vegetable production, what would be the economic benefits?
- What is the influence of new technologies, such as wide-span tractors, on the economic viability of controlled traffic in vegetable production?

Chapter 6. Future directions

The preceding chapters highlight both challenges and benefits associated with the adoption of controlled traffic in vegetable production. Chapter 6, comprised of two previously published papers, attempts to look to the future by visiting the past to outline possible approaches to overcoming the challenges present in the industry. Given some of the mechanisation challenges associated with progress towards controlled traffic in the vegetable industry, it is important to consider what options might be available to facilitate controlled traffic, or, alternatively, how to reduce compaction and improve soil management in the absence of controlled traffic.

The research questions addressed in Chapter 6 are:

- What are the future possibilities and their challenges for mechanisation that would allow fully integrated controlled traffic systems for mechanised vegetable production?
- Are there other opportunities for reducing soil compaction avoidance, either in, or outside of, a controlled traffic system?

Chapter 7. Summary and Conclusion

Chapter 7 summarises the papers that comprise the thesis and highlights some of the key issues that would influence future development of controlled traffic in the Tasmanian vegetable industry and would also be applicable to other vegetable production areas.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Land degradation, defined as the reduction and loss of soil function, is a key issue facing global agriculture in an environment of increasing demand for food and fibre, and decreasing natural resources (Chen et al., 2002). Gaining a measure of the extent of land degradation seems almost impossible, with a variety of inclusions and exclusions of land use type and methodologies used. Global estimates range from less than 1 billion ha to more than 6 billion ha (Gibbs & Salmon, 2015). There is also wide disagreement about the spatial distribution of land degradation.

The first global effort to map land degradation was the Global Assessment of Human-induced Soil Degradation (GLASOD) conducted from 1988-1991 (Oldeman et al., 1991). A total of 12 types of soil degradation were classified under four broad categories: water erosion, wind erosion, chemical deterioration (including loss of nutrients and/or organic matter, salinisation and acidification) and physical deterioration (including compaction, sealing, crusting and waterlogging). All these processes occur naturally, although generally very slowly in most environments that are not subject to human impact. Their severity and consequences are exacerbated by human activity. With only about 11% of the soil covered land surface area used for crop and animal production (Chen et al., 2002), loss of productivity through soil degradation is a global concern.

From a cropping perspective, erosion and compaction are dominant forms of land degradation that are accelerated through the application of mechanized production systems – erosion through the over-use of tillage, and compaction through the inexorable increase in machine power and weight as producers chase greater levels of operational efficiency. Compaction caused by machinery traffic is often the reason for intensive tillage operations as part of the process of soil rejuvenation and seedbed creation (McPhee et al., 1995b). The inescapable link between traffic and tillage was recognized in the 1960's when it was noted that 'the mechanisation of agriculture may have encouraged a commonly accepted level of excessive traffic necessitating excessive tillage' (Arndt & Rose, 1966) – and that was at a time when the weight of the most commonly used tractors was <20% of their current day equivalents.

2.2 Soil compaction, mechanisation and controlled traffic

Mechanised agriculture is directly responsible for degradation of the soil resource through impacts such as compaction, structural decline and erosion, a point that has been widely researched and recognised for well over 50 years (Flocker et al., 1960; Hubbell & Gardner, 1948; Weaver & Jamison, 1951). Soil compaction in crop production can be managed by remediation (mechanical or biological tillage), minimisation (low ground pressure traction and load support systems) or avoidance (controlled traffic). There is a long history of research into tillage as a means of soil compaction remediation, with thousands of peer reviewed papers published on the topic. Low ground pressure track and tyre traction systems have also received considerable research and commercial attention (Ansorge & Godwin, 2007; Antille et al., 2013; Arvidsson & Keller, 2007). Zero-till techniques in grain production were initially seen as a key factor in reducing soil compaction as a result of the reduced amount of traffic in the field. However, simple traffic modelling shows that even in large scale zero-till grain production using wide equipment, machinery operating in random traffic systems may lay down load bearing wheel tracks on >50% of a field each season (Kroulik et al., 2011; Newell et al., 1998). In vegetable production, the cumulative area tracked per season can be as high as five times the area of the field (Domzal et al., 1991; Kuipers & Zande, 1994).

Despite all the investigations into tillage, alternative traction systems and zero-till, no system has proved as effective for rehabilitation and improvement of the soil resource, or for providing wide ranging benefits that extend to the entire production system, as controlled traffic (Chamen, 2015; Tullberg, 2010). Traffic management leading to the isolation of soil compaction from the crop growth zone, is the original *raison d'être* of controlled traffic. However, research and commercial experience has shown the benefits of adopting controlled traffic are cumulative and synergistic, extending to virtually every aspect of the production system.

2.3 History – research, development and adoption

Despite early efforts in the 19th century (Halkett, 1858), the concept of controlled traffic seems to have disappeared from the published literature with the transition from steam power to internal combustion engines, and the arrival of lighter, more compact tractors. It was not until the late 1960s that interest was re-kindled after observations that cotton yield responses to deep ripping effectively disappeared after three years of wheel traffic (Cooper et al., 1969). Despite tractors being much lighter than they are today, plant growth improvements were apparent when compaction was excluded from the area growing the crop (Taylor & Bruce, 1968). Controlled traffic became an academic research tool, allowing plant growth to be studied free of the effects of soil compaction.

Since that time, research has been reported on all aspects of controlled traffic – crop growth and yield (Gerik et al., 1987; Qingjie et al., 2009), soil physical and biological impacts (Chamen et al., 2010; Galambosova et al., 2012; McPhee et al., 2015; Rodgers et al., 2018; Stirling, 2008), energy use (McPhee et al., 1995b; Tullberg, 2000), machinery (McPhee et al., 1995a; Morrison, 1985), environmental benefits (Ball et al., 1999; Tullberg et al., 2018), economics (Kingwell & Fuchsbichler, 2011; McPhee et al., 2016; McPhee & Pedersen, 2017; Stewart et al., 1997) and adoption (T. Chamen, 2009; Tullberg et al., 2007) across the grain (Galambosova et al., 2017; Tullberg, 1994), cotton (Bennett et al., 2017; Dumas et al., 1973), sugar cane (Braunack & McGarry, 2006; Garside et al., 2004), vegetable (Hefner et al., 2019; Lamers et al., 1986; McPhee & Aird, 2013; McPhee et al., 2015; McPhee et al., 2013), forage (Hargreaves et al., 2019; Neale & Tullberg, 1996) and other industries (Chamen, 2008). Despite the obvious advantages, and the efforts of a few isolated pioneers in various parts of Australia, controlled traffic remained a topic largely of academic research interest into the 1990s.

Significant commercial adoption of controlled traffic farming commenced with a dedicated adoption project in the Central Queensland grains industry in the mid-1990s (Chamen, 2008; Tullberg et al., 2007). While research has provided evidence of the benefits of controlled traffic, farmers have provided the lead in adjusting machinery to make the system functional at the farm level. Early systems, which pre-dated the availability of GNSS guidance, provided visual guidance by removing cultivating and seeding tynes that followed the tractor wheels, thus leaving the wheel tracks uncropped, which provided a visible path for in-season spray operations and harvest (Chapman, 1998; Chapman et al., 1995). Growers also led the way in modifying machinery, the most obvious change being the extension of tractor axles to match the track gauge of grain harvesters, which has been 3 m (or 120 inches) for many years, but is now gradually increasing as manufacturers change designs to deliver higher capacity (Anon., 2000; Isbister et al., 2013). There are now a number of manufacturers supplying CTF compatible equipment into the grains industry based on 3 m track gauge modules, either ex-factory, or as after-market kits and modifications. Adoption of CTF varies across the different grain growing regions of Australia, and uptake in specific areas can often be attributed to the efforts and influence of dedicated individuals (Chamen, 2008; Isbister et al., 2013). Estimates vary, but current uptake of CTF in the Australian grains industry is reported to be in the order of 30% (Umbers, 2017), although there is some doubt over these statistics. Closer investigation of the data indicates high levels of adoption in some regions (e.g. Tasmania) where local knowledge indicates adoption is basically non-existent. This difference probably reflects poorly designed questions and interpretation due to a persistent and wide-spread mis-understanding of what actually constitutes controlled traffic – i.e. the continuing belief in some quarters that RTK GNSS guidance, which has been widely adopted across most crop production sectors (Umbers, 2017), is a sufficient criterion on which to claim use of controlled traffic, without any thought given to the need for dimensional integration of machinery.

Uptake of CTF overseas lags that in Australia. UK farmers face constraints on vehicle width because of road transport regulations, making it difficult to match tractor and grain harvester track gauge, as their Australian counterparts have done (Chamen, 2003). A range of alternative layouts have been developed to achieve the best track matching possible given the challenges of dimensional integration (Chamen, 2009; Chamen, 2009), leading to significant success in adoption, although the area of wheel track is substantially more than the 10-15% achieved on Australian grain farms. There has been very little uptake of CTF in the North American grain industry, notable exceptions being a small number of farmers in Iowa, USA (Mitchell, 2007) and Alberta, Canada (Gamache, 2013; Larocque, 2013).

Interest in controlled traffic in the Australian sugar industry began with the Sugar Cane Yield Decline Project (1993-2006), which identified a number of strategies to reverse the yield decline of long-term monocultural sugar cane cropping (Garside, 1997; Garside & Bell, 2006). These strategies included break crop rotations, minimum tillage and controlled traffic. Sugar cane harvest operations have a large traffic footprint. With total track width per pass representing approximately 50% of machine width, and mismatches between traditional cane row spacing (1.5 m) and the track gauge of harvesters and haul-out bins (1.8 m), the smallest area of field tracks that can be achieved with perfectly straight driving is 70%, and up to 90% with driver error in the absence of GNSS guidance. The most successful approach to CTF in the sugar cane industry has been to change the row configuration of the crop to better match the track gauge of harvest machinery, which will reduce tracked area to approximately 33% for the harvester. However, implementation of fully effective CTF also requires guidance of the haul out vehicle, otherwise the tracked area is likely to be closer to 50%. Indications are that adoption of guidance on harvesters is ~50%, while adoption of alternative crop configurations to enable CTF is ~30%. Adoption of guidance on haul outs is ~1%, so while progress has been made with integration of the harvester and crop configuration, there is still a long way to go to achieve a functional CTF system (C. Norris, Norris Energy Crop Technology, pers. com.).

The vegetable industry is another industry that faces many challenges in the uptake of controlled traffic. A diverse range of crops grown requires a diverse range of machinery designs, particularly for crops that are mechanically harvested (McPhee et al., 2018). Hand-harvested crops present fewer challenges. Production systems based on beds lend themselves to controlled traffic (Rogers et al., 2001; Vedie et al., 2008), although many such systems are routinely cultivated and re-formed after each crop without consideration of the potential benefits of maintaining permanent beds and traffic lanes. For machine harvested crops, adoption of controlled traffic is more difficult, although progress has been made by one Australian operator using custom-designed bean and sweet corn harvesters with a 3 m track gauge and working width to match grain CTF systems (Johanson, 2020). This system works because of a relatively simple vegetable cropping rotation of sweet corn, green beans, hand-harvested broccoli and grain crops.

Another approach that has found favour in the vegetable industry is the use of Seasonal CTF (SCTF) (Vermeulen et al., 2010). This approach recognises the difficulties of integrating a number of dimensionally incompatible harvesters in order to maintain distinct, permanent traffic lanes. In SCTF, all non-harvest operations (e.g. tillage, seedbed preparation, crop management) are performed with dimensionally integrated machinery based on permanent wheel track locations and a track gauge that spans one or two beds. Harvest operations are performed by conventional machinery with no regard to controlled traffic principles. SCTF has only become a realistic option with the advent of RTK GNSS guidance, making it possible for operators to return to the precise location of wheel tracks used in the previous season, despite the fact that they may no longer be visible as a result of high traffic intensity harvest operations and (in the case of root crops) high soil disturbance.

The application of controlled traffic is not limited to large-scale mechanised agriculture. As noted in Chapter 1, it was probably first 'invented' by those who tilled the soil by hand. Trials of permanent raised beds in small-scale farming in eastern Indonesia showed the potential to enhance food security and reduce erosion and labour requirements (Van Cooten & Borrell, 1999). The beds were initially formed and then maintained using hand labour or, where mechanisation was available, two-wheel hand tractors.

2.4 Minimum requirements for controlled traffic

Dimensional integration of machinery track gauge and working width is a key requirement for the success of controlled traffic. As explained by Baker et al. (2007), this is met by 'machines having the same track gauge and compatible working widths, and then constraining their movement in the field to permanently defined and located wheel-tracks'. It is not actually necessary for all machinery to have the same track gauge, provided dimensions of track gauge and implements are confined to compatible modules of width. Another important factor for the success of controlled traffic is the ability for all machinery to stay on the tracks. This can be a particular challenge in undulating topography, wet conditions or situations of track degradation through rutting or erosion (Isbister et al., 2013). GNSS RTK guidance and autosteer have become important enabling technologies for accurate traffic and implement control and are particularly relevant to the maintenance of tracking accuracy in controlled traffic systems (Thomasson et al., 2019). However, guidance technologies in themselves do not make a controlled traffic system. They are an enabling technology, and the fundamental basis of controlled traffic is the dimensional integration of machine track gauge and implement working width across all machinery used in field operations.

Layout is another important aspect of controlled traffic. It influences field logistics and efficiencies (Bochtis et al., 2010; Bochtis et al., 2010; Bochtis et al., 2009), and runoff and drainage (Isbister et al., 2013; McPhee et al., 2013; Neilsen, 2008).

In summary, controlled traffic farming (CTF) can be defined by the following fundamental points (ACTFA, 2018):

- All machinery has the same or modular working and track gauge width which allows establishment of permanent traffic lanes.
- All machinery is capable of precise guidance along the permanent traffic lanes.
- Farm, paddock and permanent traffic lane layout is arranged to optimise drainage and logistics.

2.5 Benefits

Although the concept of controlled traffic arose from a desire to avoid the negative impacts of soil compaction, it is now recognized and proven that the advantages go well beyond that single issue. Research and commercial experience in a wide range of environments has provided evidence of improvements in soil physical and biological properties, soil-water relations, water and nutrient use efficiency, operational timeliness, yield and economics, along with reductions in soil erosion, greenhouse gas emissions, energy use, tillage requirements, and equipment capital and operating costs (Antille et al., 2015; Antille et al., 2019; Braunack & McGarry, 2006; Carr et al., 2008; Chamen et al., 1992; Halpin et al., 2008; Kingwell & Fuchsbichler, 2011; McPhee et al., 1995b; McPhee et al., 1995c; Neilsen, 2008; Stirling, 2008; Tullberg, 2000; Tullberg, 2010; Tullberg et al., 2001). Notwithstanding the many benefits, every production, environmental and economic advantage of controlled traffic stems from the isolation of traffic compaction into defined, permanently located zones, and the absence of traffic compaction in the friable soil zones between the wheel tracks.

Regardless of the industry sector considered, the benefits of controlled traffic extend to the entire cropping system. There are many connections between the isolation of soil compaction from crop growth zones and the flow-on benefits to the farming system. This makes it difficult to isolate many of the benefits into discipline-related foci. Nevertheless, the following summary of benefits is structured under broad topic areas in an effort to provide some logic and cohesion to the issues.

2.5.1 Soil

Soil compaction resulting from random traffic movement is probably the largest management induced variable impacting crop production. It is ironic that the use of tillage to produce uniform soil conditions for the subsequent operation of machinery (e.g. seeders) and growth of crops inevitably creates zones of underlying nonuniformity in the form of random traffic compaction that may or may not have been ameliorated by management intervention or natural processes (Carter et al., 1987). In most mechanised farming systems, the randomness of traffic leads to unpredictable spatial variability of soil compaction (Barik et al., 2014). Changes to soil structure due to compaction are a significant precursor to in-field crop variability (Chamen, 2009), the mitigation of which fuels interest in precision agriculture techniques that often focus on zonal management and variable rate application of crop inputs. Although natural factors such as soil texture also contribute to in-field crop variability, it is unlikely that vari-rate approaches will ever completely ameliorate variability until the impacts of soil compaction are resolved.

The impacts and extent of traffic compaction vary with soil texture (Díaz-Zorita & Grosso, 2000; Voorhees, 2000), degree of pre-existing compaction (Håkansson et al., 1988), organic matter content (Reichert et al., 2018; Soane, 1990), seasonal factors such as soil moisture (Håkansson et al., 1988; Hamza et al., 2011; Voorhees et al., 1985), vehicle loads, running gear and number of traffic passes (Ansorge & Godwin, 2007; Ansorge & Godwin, 2008; Antille et al., 2013; Botta et al., 2006; Braunack & Johnston, 2014; Håkansson, 2005; Naderi-Boldaji et al., 2018), tillage management system (Botta et al., 2012; Celik et al., 2017; Voorhees & Lindstrom, 1984) and crop (Chan et al., 2006; Wolfe et al., 1995). Despite considerable investment over many years in research, development and design of vehicle running gear , countless studies of the interactions between soil, contact pressures, axle loads and tillage, and the development of various soil compaction models to aid management of traffic and tillage (Alakukku et al., 2003; Ansorge & Godwin, 2007; Ansorge & Godwin, 2008; Håkansson & Reeder, 1994; Keller, 2005; Keller et al., 2015; McGarry, 2003; O'Sullivan et al., 1999; Vermeulen & Klooster, 1992; Vero et al., 2014), no system other than controlled traffic has managed to completely remove the deleterious effects of traffic on cropping soil, or ameliorate the long-term impacts of subsoil compaction.

The absence of compaction in the crop growth zones of controlled traffic systems impacts every aspect of soil-water-plant relations. Improved infiltration has been reported under controlled traffic in both irrigated (Boulal, et al., 2011; McPhee et al., 2015) and rain fed (Blanco-Canqui et al., 2010; Hussein et al., 2018; Li et al., 2001; Li et al., 2009) cropping systems, with increases of at least an order of magnitude being measured. As a consequence of improved infiltration, runoff and subsequent erosion and off-site pollution is reduced (Boulal, et al., 2011; Li et al., 2007; Masters et al., 2013; Titmarsh et al., 2003; Tullberg et al., 2001; Wang et al., 2008). In contrast, Reyes et al. (2005) found no difference in runoff between no-tillage treatments that were differentiated by the presence or absence of traffic, except when the site was subjected to 50-100 year rainfall events. While they concluded there was no significant advantage to controlled traffic in the circumstances of their research, the reduced runoff under high intensity rainfall conditions may become very significant with the prediction of increased extreme weather events induced by climate change. There is a risk in some circumstances of increased runoff and erosion from the compacted wheel tracks that are a consequence of controlled traffic management (Basher & Ross, 2001; Silburn & Glanville, 2002). The importance of these differences is situation dependent and there are examples where downslope CTF layouts have significantly outperformed conventional zero-till and contour banks in terms of reduced erosion (Cannon, 1998; Neilsen, 2008; Whale et al., 2007; Yule, 1998).

Improvements in infiltration have also been accompanied by improved soil water retention characteristics (Blanco-Canqui et al., 2010; McHugh et al., 2009; Yadav et al., 2020), which has implications for the storage of plant available water in both rain-fed and irrigated cropping. The changes in soil-water properties under controlled traffic extend to improvements in hydraulic conductivity (Blanco-Canqui, 2010; Bai, 2008) and consequently internal drainage of the soil. All these factors are linked to improvements in soil porosity (Bai et al., 2009; Lamers et al., 1986), leading to improvements in aeration. This has the flow-on effect of being beneficial to soil biology (Pangnakorn et al., 2003; Rodgers et al., 2018; Stirling, 2008). There are very few peer-reviewed reports of the impacts of controlled traffic on soil biology. Many of the potential benefits have to be deduced from the results of work investigating the negative effects of traffic, as opposed to the positive effects of the absence of traffic. Reviews and research papers show that while impacts on soil biology vary as a consequence of climate, soil type and agricultural management system, the overwhelming evidence is that, more often than not, traffic-induced soil compaction has negative consequences for soil biology (Beylich et al., 2010; Brussaard & van Faassen, 1994; Whalley et al., 1995).

Another benefit that flows from the absence of compaction and improved drainage and aeration is the reduction in greenhouse gas emissions from denitrification of nitrogenous fertilisers and production of methane from soil biological processes. Denitrification processes and methane production are aided by compacted conditions, which are often associated with high soil moisture situations, particularly when water filled porosity is high (Ball et al., 1999; Beare et al., 2009; Ruser et al., 1998). Consequently, the improved drainage, porosity and aeration characteristics of uncompacted soils managed under controlled traffic should be less conducive to denitrification and methane production. This has proven to be the case in a range of production environments, including barley production in Scotland (Ball et al., 1999), vegetable production in The Netherlands (Mosquera & Hilhorst, 2005; Vermeulen & Mosquera, 2009) and grain growing in Australia (Tullberg et al., 2018).

The enhanced soil structural conditions arising from the use of controlled traffic have also been shown to improve fertilizer use efficiency. Research with rain-fed sorghum grown in CTF and non-CTF circumstances has shown improvements in Nitrogen Use Efficiency (NUE) of up to 60% (Hussein et al., 2018), with the authors concluding that soil compaction will always limit NUE until its impacts are removed from the crop root zone.

Elimination of the need for compaction removal tillage under controlled traffic makes it easier to reduce overall tillage requirements and, with access to appropriate equipment, retain crop residues for soil protection and erosion control. This could have important benefits in vegetable production which often relies on intensive tillage to remediate harvest traffic compaction. The adoption of controlled traffic enables retention of residues from cash or cover crops as an important contribution to reducing soil erosion and building soil structure (Rogers et al., 2004). Even if residues are not retained, the reduced tillage needs of controlled traffic lead to important benefits for soil structure and biology (Vedie et al., 2008).

2.5.2 Yield

A prime concern of producers when considering new approaches to farming is the opportunity to increase yield, or at the very least, reassurance that yields will not decrease. Controlled traffic research has reported yield increases for many crops, including forage and a range of grains and vegetables (Arvidsson & Hakansson, 2014; Botta et al., 2018; Dickson & Ritchie, 1993; Dumas et al., 1975; Esteban et al., 2019; Galambosova et al., 2017; Hefner et al., 2019; Hussein et al., 2018; Jensen et al., 2001; Lamers et al., 1986; Li et al., 2014; Neale & Tullberg, 1996).

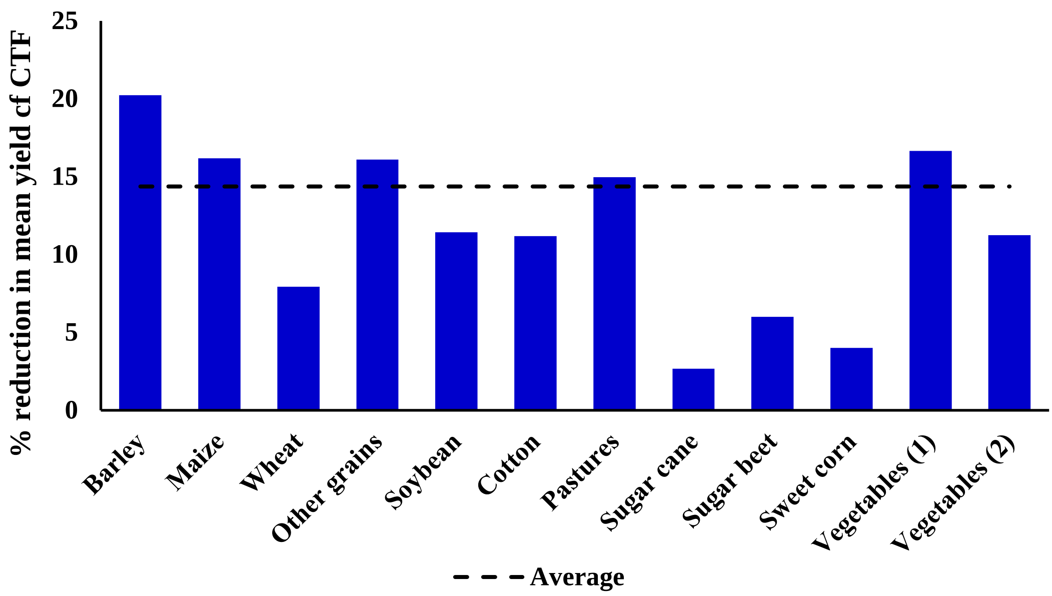

Figure 2-1. Mean % reduction in crop yield due to the impacts of traffic-induced soil compaction. Vegetables (1) includes beans, peas, spinach and cabbage. Vegetables (2) includes beetroot, carrot, onion and potato. Average represents the average of all individual experiments included in the analysis. Adapted from Chamen (2011) and expanded with more recent data.

Figure 2-1, adapted from Chamen (2011), and added to with data reported since 2011, illustrates the range of yield reductions recorded for a variety of crops grown under conditions of compacted and non-compacted soils. Some of these data are the results of compaction investigations while others represent comparisons of CTF and non-CTF systems. These data come from an analysis of 72 peer-reviewed papers and conference proceedings from 33 countries reporting on 146 experiments conducted on soils ranging from sand to silt loam to heavy clay (Appendix A). The least represented crop is canola (one experiment) and the most is maize (27 experiments), closely followed by wheat (24). Across all experiments, the average yield reduction due to random traffic was 14.4%.

There are fewer reports in the literature regarding the impact of controlled traffic on the yield and quality of vegetables as compared to grain crops. Vedie et al. (2008) noted that permanent beds produced no difference in crop yield, and for root crops, resulted in lower quality as a result of deformities. It is proposed that this effect was due to consolidation of the crop bed in the absence of mouldboard ploughing, since it is not a suitable tillage technique for permanent beds. Tyned implements were used on the permanent beds, but the increase in soil compaction noted at depths of 10-30 cm suggest that tillage operations were confined to the surface layer. In naturally consolidating soils, it may be necessary to conduct occasional remedial tillage operations to a greater depth, even with the implementation of controlled traffic. The other improvement that should be possible with the use of controlled traffic is the retention of more organic material, whether from crop residue or cover crops, which may help resist consolidation.

Potatoes grown under a controlled traffic system produced an increase in both yield and quality in Scotland (Dickson et al., 1992). Comparing controlled traffic and conventional production systems, total yield of ware (market) potatoes increased by 14%, and marketable yield by 18%. Yield increases ranging from 3% for ware potatoes to 7% for seed potatoes under controlled traffic in The Netherlands have been reported (Lamers et al., 1986). Recent Danish studies covering four vegetable crops (cabbage, potato, beetroot, squash) at four sites over two seasons showed statistically significant marketable yield increases due to CTF in one season, but not the other, with the suggestion that seasonal conditions had an effect (Hefner et al., 2019). Marketable yield increases of 27% for cabbage, 42% for beetroot and 70% for potato were recorded for CTF compared to random traffic. In Tasmanian research, controlled traffic management gave a statistically significant increase in onion yield, but no significant differences were recorded for broccoli, beans and carrots over a three-year rotation (McPhee et al., 2015).

2.5.3 Root crop harvest benefits

In addition to the soil improvements outlined above, root and tuber crop harvest is a very specific scenario which stands to benefit from controlled traffic. The operation that is most dependent on efficient soil separation is potato harvest. Current methods of potato production, which require recovery of tubers from a mound of soil, need to lift and sieve ~1,500 m^3 of soil per hectare (McPhee et al., 2018). This soil is generally friable, the result of tillage and mound formation processes at the time of sowing, and moist at the time of harvest, with a density of ~1 Mg/m^3. Harvest therefore requires uplift and sieving of ~1,500 Mg/ha of soil, for the recovery of 40-80 Mg/ha of potatoes – generally ~20-40 Mg of soil per Mg of tubers.

Despite the intensity of cultivation at the time of mound formation, potato fields are subject to soil compaction during the growing season. This may be the result of traffic during pre-sowing tillage operations, the sowing operation itself, and spraying and fertilizing operations. A controlled traffic system that precedes, and lasts beyond the duration of, the growing season would isolate pre-sowing tillage and sowing compaction from the crop zone and hence influence clod formation. In-season spraying and fertilising traffic is already effectively conducted on a seasonal controlled traffic basis.

Data on the relationship between controlled traffic and clods in potato harvest are rare, but telling. At loam and light clay sites in the Netherlands, potatoes harvested from a controlled traffic system had 27% less soil tare compared to a conventional system (Lamers et al., 1986). Experiments on loam over sandy clay loam soils in Scotland showed 30% more clods in rows impacted by traffic compared to those without traffic impacts (Dickson et al., 1992). There was a significant difference in the amount of clod recovered at harvest, with the conventional treatment yielding 34% more clods than controlled traffic. Clod load varied from 17% to 54% over the three years of the work. Dickson et al. (1992) noted that the reduced clod load had the potential to simplify and lighten harvester design, and possibly permit higher harvest travel speeds, although no such developments have occurred in the industry, as they would be dependent on the wide spread adoption of controlled traffic. Commercial experience on a clay loam soil in New Zealand showed a reduction of 45% in the amount of soil transported from the field under controlled traffic, with subsequent benefits of reduced washing time, energy and waste water at the packhouse (Powrie & Bloomer, 2010). Potatoes from the adjacent conventional production system operated in the same field often required a double wash, compared to a single wash for potatoes produced under controlled traffic. It is reasonable to conclude that these post-harvest advantages would reduce processing costs and would also be applicable in other potato growing areas of the world where production is based on clay textured soils.

A further aspect of potato harvest that could prove beneficial to a controlled traffic system is stone windrowing (Misener & McLeod, 1986). This is a pre-planting process in which the seedbed is sieved with a tractor-towed machine and stones larger than the gaps in the sieving web are conveyed to the inter-row furrows. Stone windrowing could provide a foundation for firm wheel tracks for subsequent controlled traffic operations.

2.5.4 Timeliness and trafficability

Apart from removing or reducing the direct effects on crop yield caused by wheel traffic and soil compaction, controlled traffic management has another impact that often leads to improved yield of the overall farming system – improved timeliness. Timeliness is a measure of the ability to perform key management operations at the optimum time. It is an important consideration for operations such as seedbed tillage, sowing, spraying and harvest in most cropping enterprises. Sometimes operations may have to take place within a very narrow time frame (e.g. to achieve harvest at the desired crop maturity and quality, or to meet supply schedules for fresh or processed vegetables). On other occasions, there may be a relatively large time window (e.g. acceptable planting period of several weeks duration), but weather conditions may limit the time available for field work. The timeliness benefits of controlled traffic, and particularly when combined with zero-till, allow for greater opportunity cropping and overall increased yield (Yule & Radford, 2003). This has been demonstrated in field experiments (McPhee et al., 1995c) and predicted through modelling (Li et al., 2008).

Timeliness can be improved by: 1. working faster (increased speed and/or increased implement width); 2. starting operations earlier (in the day, in the season or after rain); 3. reducing the number of operations required (McPhee et al., 1995c). Controlled traffic systems can improve timeliness through all of these avenues by virtue of the following changes to operations and management:

1. Working faster – compacted traffic lanes reduce rolling resistance and improve traction (Burt et al., 1986; Taylor, 1983), while the absence of compaction in crop zones reduces tillage draft (Dickson & Ritchie, 1996; McPhee et al., 1995b;

Tullberg, 2000). The combination of effects allows faster travel speeds and/or wider machinery.

2. Starting operations earlier – provided ponding of runoff in wheel tracks is prevented by good layout design and adequate surface drainage, compacted traffic lanes allow earlier access to the field after rain or irrigation, while minimising rutting or soil damage (Dickson & Ritchie, 1996; McPhee et al., 1995c; Spoor et al., 1988).

3. Reducing the number of operations required – it is widely recognised that controlled traffic reduces the need for intensive post-harvest remedial tillage as a precursor to seedbed preparation, thereby reducing the number of operations needed. In many crops, particularly grain, controlled traffic enhances the adoption of zero-till techniques (Tullberg et al., 2007). Similar timeliness advantages have been observed in cane production (Price et al., 2004). There are opportunities to adopt reduced or zero-till in vegetable production in conjunction with controlled traffic and thereby capture these timeliness advantages in the vegetable sector (McPhee et al., 2015; Vedie et al., 2008).

Improving timeliness in vegetable production systems can be challenging, as they often rely on numerous tillage operations to alleviate soil compaction caused by heavy harvest machinery and prepare a seedbed for the next crop. Harvest of vegetable crops almost always takes place on the timetable of the customer, rather than being dictated by the appropriateness of the soil condition for harvest operations. Consequently, at wet times of the year harvest operations can cause considerable soil damage through rutting and compaction of soil that was intensively tilled at the start of the cropping season. This necessitates additional intensive remedial tillage before the next crop can be established. Such soil management systems often fail to satisfy timeliness requirements, particularly in regions where frequent rainfall coincides with seedbed preparation.

One of the many factors affecting crop yield potential is the length of the growing season, which is influenced by both the planting or sowing date, and the harvest date. In situations that rely on tillage to form a seedbed, a common scenario in vegetable production, the earliest date of sowing or planting is often determined by soil trafficability and workability. If these operations have to be delayed, length of the growing period is shortened, and the potential crop yield is reduced (Boone & Veen, 1994). Management systems such as controlled traffic, which improve trafficability and reduce the amount of seedbed preparation required (McPhee et al., 2015), can offer substantial advantages in terms of potential crop yield. In temperate regions, where winter cropping may be limited, timeliness at spring time sowing can be improved by preparing raised beds in autumn (Rowse & Goodman, 1984).

2.5.5 Energy use

Tillage has been a part of crop production practices since the beginning of agriculture. Tillage is undertaken for a variety of reasons, such as removal of compaction, weed control, crop residue incorporation and seedbed preparation. The last of these, seedbed preparation, is one of the most important reasons for tillage – to produce a loose, friable soil suitable for seedling emergence and plant growth. The process of seedbed preparation often starts with tillage to remove the compaction caused by previous traffic, most commonly that which occurs during harvest. This is particularly the case in vegetable production systems, many of which rely on heavy harvest and transport machinery operating in moist soil conditions to deliver produce in a timely manner to markets or processors. A considerable amount of research effort has been, and continues to be, invested in attempts to minimize the impact of traffic compaction and optimise the performance and outcome of tillage operations while continuing to allow random traffic movements in the field (Batey, 2009; Botta et al., 2006; Godwin, 2009; Raper & Reeves, 2007).

Energy is used in two ways during tillage: (1) to drive the tractor (traction, rolling resistance and wheel slip), and (2) to pull the implement (draft). When operating on a cultivated surface, some of the energy output of a tractor is absorbed into the soil in the wheel tracks, resulting in soil compaction. This compaction then increases the draft load on the implement. Research has shown that individual tyne draft increases two-fold when following a preceding wheel (Tullberg, 2000). Depending on the size and type of implement, this can lead to a 30% increase in total implement draft load. This is in accordance with other findings showing that compaction resulting from a single pass of a tractor wheel over freshly tilled soil can increase total implement draft by up to 25% (Voorhees, 1979) and controlled traffic can lower draft by 25% (Lamers et al., 1986). Consequently, approximately 50% of the tractor’s power may be consumed in creating, and then removing, its own compaction (Tullberg, 2000).

Various researchers have shown energy savings, both for individual operations and on a seasonal basis, ranging from 30-70% when comparing controlled traffic to conventional practices (Ball & Ritchie, 1999; Burt et al., 1986; Dickson & Ritchie, 1996; Lamers et al., 1986; McPhee et al., 1995b; Trouse et al., 1985). In addition, the peak energy demand (i.e. that required for the most energy intensive operation) can be substantially reduced, to the extent that total tractor power requirements (and hence size and capital cost) may be reduced by 65%-85% in some cases (McPhee et al., 1995b).

Apart from improved traction and lower draught, controlled traffic can give further reductions in energy use by avoiding the need for deep ripping. These operations are expensive in energy terms, and of limited long-term benefit (Botta et al., 2006; Spoor, 2006; Spoor et al., 2003) unless accompanied by the implementation of controlled traffic after ripping.

The absence of compaction in the crop zone may also allow changes to be made to tillage practices which result in further draught reductions. Research in the Netherlands showed that controlled traffic allowed a 20% reduction in tillage depth (Lamers et al., 1986), which leads to large decreases in draft (Godwin, 2007). Apart from differences such as reduced depth for tillage operations, controlled traffic can also offer considerable energy savings by allowing changes to the type of tillage undertaken. Most conventional tillage systems rely on multiple passes of several implements to prepare a seedbed. Since controlled traffic removes the need for "compaction removal tillage", the number of operations required to produce a seedbed may be reduced, in many cases allowing the uptake of zero-till techniques (McPhee et al., 2015; Potter & Chichester, 1993).

Soil compaction cannot be eliminated in mechanized agriculture. It can only be managed. Controlled traffic offers an energy efficient means of managing soil compaction, while also providing significant benefits in other aspects of crop production.

2.5.6 Economics

The commercial uptake of CTF in the Australian rain-fed grain industry has been largely grower driven, and once the change is made to CTF, there is very little opportunity to compare, side by side on the same farm, the performance of CTF and non-CTF systems (Tullberg et al., 2007). Consequently, rigorous studies and reviews comparing the economics of CTF to conventional production systems are uncommon.

An early Australian study of the economics of CTF was based on data from experimental work with grain production in south-east Queensland. Analyses using economic data relevant to the period showed that conversion to CTF would produce internal rates of return (IRR) ranging from 13.5% to 18.9%, based on a number of variables such as savings/ha and discount rate (Bright & Murray, 1990).

Another early economics study involved the modelling of UK grain cropping systems using different conventional and zero-traffic management approaches and differing inventories of machinery (Chamen & Audsley, 1993; Chamen, Audsley, et al., 1994). A feature of this study was the inclusion of both tractor- and gantry-based controlled traffic systems, which were compared against conventional tractor-based production systems. Economic modelling showed that implementation of controlled traffic would provide greater improvements in farm gross margin on heavier (clay) soils than on medium textured soils. It was estimated that unpowered tillage equipment used in controlled traffic systems could be 35% cheaper than conventional system equivalents. This is primarily due to the reductions in draft load arising from better soil conditions, thereby providing the opportunity for equipment of lighter construction. All of the CTF systems modelled in this study relied on yield increases to pay for the transition costs and maintain profitability.

Despite yield increases, reductions in tractor power requirements and more favourable potato harvest conditions, an economic analysis based on the work of (Dickson et al., 1992) found no significant gross margin advantage for potato production as a result of zero traffic, primarily because of the high level of seasonal variability in gross margins (Stewart et al., 1997; Stewart et al., 1998). Gross margin analysis for other crops in the research rotation showed significant improvements for the controlled traffic system, with spring barley, winter barley and oil seed rape gross margins being respectively 23%, 35% and 42% higher than conventional traffic systems. All of the CTF system crop gross margins were also significantly higher than the gross margins for low ground pressure traffic systems used in the research.

Growers who use controlled traffic farming often comment that the advantages of the system are most apparent when the seasons are worst, either wetter or drier than normal. This observation is reflected in case study modelling of a grain cropping enterprise in the South Burnett region of Queensland, in which controlled traffic provided a 40% increase in yield in poor seasons, a 10% increase in average seasons and no change in a good season (Mason, 1995). With 30% lower fuel consumption, smaller tractors and reduced labour, the model showed that the combination of CTF and zero-till would increase profit by 30% and reduce equipment investment by almost 30%.

Savings in operating and capital costs were evident in controlled traffic for irrigated grain crops in a semi-arid tropical environment (Burdekin River Irrigation Area, Queensland) (McPhee et al., 1995b). Significant reductions were recorded for both total and peak tillage power requirements. When applied to machinery investment decisions, the reductions in power 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 controlled traffic and zero-till extended beyond the reduction in power requirements. Improved timeliness due to CTF allowed more frequent and reliable crop production, further enhancing the economic potential of the system.

A case study of a northern NSW mixed grain farm employed partial budgeting to estimate the benefits of adopting controlled traffic as a further advance on existing no-till practices (Scott, 2008). Changing equipment and practices purely to avoid overlap showed a 51% return on marginal capital. Drawing on research and experience that indicates various levels of yield increase as a result of CTF, yield improvements of 5-10% gave rates of return ranging from 100-160%. Analysis of a Darling Downs (Queensland) grain growing cropping group showed that increased cropping frequency, increased yield and improved grain prices (due to greater yield reliability in dry years when prices are higher) had the potential to improve gross group 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 showed the potential to nearly double the business profit level for group members.

Modelling and stepwise and sensitivity analysis were used to determine the most economically valuable aspects of CTF in the grain belt of Western Australia (Kingwell & Fuchsbichler, 2011). In the region of study, CTF was found to be most valuable on farms with compaction susceptible soils and a high level of cropping as part of the enterprise. Conservative estimates for a typical farm in the study region indicated farm profit increases of around 50% through the use of CTF.

Strahan and Hoffman (unpub. data, 2009) modelled the economic and environmental impacts of various farm management practices for grain production in the Fitzroy Basin of Central Queensland. Management options modelled were conventional cultivation practices, zero-till with random traffic, zero-till with CTF (10 crops in 10 years) and zero-till with CTF (12 crops in 10 years) reflecting the benefits of improved timeliness resulting in more opportunity cropping (Yule & Radford, 2003). Table 2-1 shows the per cent return on assets for alternative farming practices in two different farming regions in the Fitzroy Basin.

Table 2-1. Differences in return on assets modelling for different farming system approaches in the Fitzroy Basin of Queensland. (Strahan and Hoffman, unpub. data, 2009)

Catchment	Conventional	Zero-till, random traffic	Zero-till, CTF (10 crops in 10 y)	Zero-till, CTF (12 crops in 10 y)
Dawson/Callide	-2.1%	1.8%	3.2%	5.0%
Central Highlands	-2.7%	1.9%	5.4%	6.2%

The experiences of controlled traffic research in the Australian grain industry have been applied to experimental work on the Chinese Loess Plateau, an area dominated by winter wheat production grown on summer fallow stored soil moisture. Data from 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, both compared to conventional random traffic and full tillage practices (Bai 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.

Chamen et al. (2015) reported an analysis of methods to both remediate and avoid soil compaction in arable cropping systems in the UK. Compaction remediation options included subsoiling, targeted subsoiling and ploughing, while avoidance strategies included low ground pressure tyres, tracked vehicles and CTF. The only remediation strategy to give an increase in gross margin was targeted subsoiling, while all avoidance strategies improved returns. CTF, particularly on clay soils, gave the highest increase in gross margin.

Interest in controlled traffic in the Australian cane industry has increased as a result of evidence from the Sugar Yield Decline Joint Venture (SYDJV) program (Garside & Bell, 2006). A combination of controlled traffic, legume break crops and reduced and zonal tillage practices resulted in significant economic advantages for cane production. A number of different cane planting configurations were studied, selected to facilitate the application of controlled traffic in a system with severely constrained machinery modification options (Garside et al., 2004). Combinations of savings in labour and input and operating costs lifted the gross margin for the studied farming enterprise from -$5/ha (conventional system), to a range of $100-$260/ha (controlled traffic alternatives).

Information arising from the SYDJV led to changed cane farming operations for a number of growers. One example was a transition from a monoculture with conventional tillage and overhead irrigation practices, to a 3 m controlled traffic system using flood irrigation with peanuts included in the rotation as a legume break crop (Loeskow et al., 2006). Return on Investment for the farming operation changed from -10.8% to 5.9%, with projections to achieve 8% for future crops. Clearly controlled traffic was not the only change made in this farming enterprise, but it was central to the implementation of other changes, all of which contributed to the improved economic performance.

Another grower reported changing from a cane farming monoculture with conventional tillage based on single rows on 1.52 m, to dual row cane on 1.9 m using controlled traffic and a legume cash crop included as a break in the rotation (North et al., 2007). An overall economic analysis was not reported, but planting inputs changed from 6.2 to 0.9 h/ha labour (85% reduction) and 128.6 to 18.6 l/ha fuel (86% reduction). Overall, planting costs reduced by 90% (from $282/ha to $29/ha). In another case of changed cane farming practices, an improvement in farming system Return on Investment from 1.6% to 2.7% was recorded (Carr et al., 2008). The economics of the farming system improved through major reductions in land preparation and planting operations, resulting in a 54% reduction in tractor use. There was a 14% increase in gross margin, although it was noted that pest and disease control costs increased.

Another farm case study of adoption of controlled traffic and reduced (zonal) tillage in sugar cane showed an 11.8% improvement in Gross Margin, with potential for a further 6.8% increase with additional improvements to the farming system (Halpin et al., 2008). The economic analysis was also done to determine the impact of rising fuel costs (100, 125 and 150 c/l). Under these scenarios, the new controlled traffic and zonal tillage system gave relative GM advantages of 11.9%, 12.9% and 14%, compared to the previous conventional production system. At the time of the analysis, there had been a 39% reduction in tractor hours, with the potential to save another 16% through the adoption of additional improvements. Fuel use was reduced by 58%. After the change to controlled traffic, the replacement allowance for new equipment was marginally less than the replacement allowance for redundant equipment. In addition, one tractor was made redundant, resulting in a saving of $9,000/annum in replacement allowance.

It will be apparent from the examples given above, particularly in relation to the sugar industry, that the improved economics stemmed from changes to the farming system beyond simply the adoption of controlled traffic. It is important for economic reviews to recognise that often the change to controlled traffic leads to a range of changes in the farming system that would not otherwise have been possible, or at least, not as effective. This highlights the importance of analysing the system that is enabled by controlled traffic, rather than just the practice of controlled traffic *per se*.

The literature in relation to the economics of controlled traffic conversion is very much focused on the grain and cane industries. Very little economic analysis has been done in the vegetable industry. An analysis of a typical vegetable enterprise in the Lockyer Valley (Queensland) showed that even moving to seasonal CTF can provide a return on investment in the order of 38% (J. Page, unpub data). Modelling by McPhee et al. (2016) showed a range of improved returns on investment, with the magnitude of benefit influenced by current practices used on the case study farms.

2.5.7 Social

There are many aspects of farming that are often considered to be detrimental to the social and livelihood wellbeing of those involved in agriculture – long hours of work at particular times of the season, the constancy of operations that restrict opportunities to leave the farm for a holiday, fatigue and its effect on family members to name a few. Peer reviewed reporting on these matters is rare and difficult to find, but the experiences of practitioners indicate substantial benefits to be gained through the adoption of controlled traffic. A commonly reported improvement is reduced fatigue, the result of a combination of factors such as the benefits of RTK GNSS guidance, reduced tractor operating time and easier management of operations when they do occur (Grant, 1998; Holding, 2006; Walch, 2006). Some growers also report the benefits of more family time and reduced working hours – “much more family time and far less stress” and “The shift work has stopped and so has the banging and clanging in the shed at all hours” (Dunne, 2007).

The social advantages brought about by adoption of CTF can extend beyond the individual farming enterprise. Improved economics and lifestyles on individual farms have the potential to improve the overall social environment for rural communities. Further, the adoption of more advanced farming systems with the incorporation of spatial technologies has the capacity to attract younger people back to work in agriculture, whether it be on family farms or in support services in regional communities (Yule, 2005).

2.6 Disadvantages

2.6.1 Cost

Despite the many advantages attributed to controlled traffic, adoption of the principles, and the system overall, is not without its challenges. The barrier for many seems to be the cost of modifying or building/purchasing appropriate machinery. As noted earlier, grains industry CTF has matured to the stage that ex-factory and after-market solutions are available for many machinery requirements. Making a ‘clean sweep’ conversion to CTF could certainly be an expensive exercise. The most common approach is to make the transition over time, replacing existing machinery inventory with CTF-compatible machinery at the normal time of replacement and upgrade. This means the transition could take some time and is dependent on making a plan and staying with the plan until it is implemented. Estimates in the Australian grain industry suggest the marginal cost of transition, over and above the costs of like for like machinery replacement, to be generally less than $40,000 (Tullberg, 2008). Although this figure may have increased in the decade since that estimate, the marginal cost still likely represents <5% of the total capital of the machinery inventory. A number of industry case studies from the UK have shown the transition cost can be negative, with modification or new equipment purchase costs offset by the sale of equipment no longer needed, particularly as CTF allows adoption of a less intensive tillage regime (Chamen, 2015).

A comparative study in irrigated cotton showed that the costs of transition to CTF could be covered in one season, despite the requirement to change row width for the controlled traffic system (Bartimote et al., 2017). Even though in this case the CTF system gave lower yield, the financial returns were better due to improved water use efficiency (WUE) and higher quality cotton as a result of a slower maturation time.

Machinery change in the vegetable sector is far more challenging than in the grain industry, with design and machine ownership constraints impinging on the capacity for change (McPhee & Aird, 2013). In addition, the generally greater number of machines used on vegetable farms means more investment in change, even for the limited changes required for seasonal controlled traffic.

2.6.2 Erosion

Increased soil erosion is another potential disadvantage of CTF, although the issues are very site specific. In the grain growing Vertosols of Queensland and northern New South Wales, it is normal to leave the permanent wheel tracks unplanted. This was originally done to provide guidance in the pre-RTK GNSS era, although the highly compacted soil does not provide significant yield anyway. In this situation, erosion of both the untrafficked cropping soil and the wheel tracks has been reduced by appropriate layout, with wheel tracks up and down the slope. With improved infiltration in the crop growth zone, and each wheel track acting as a drainage line for its own small catchment, the volume of water carried per track is limited (Cannon, 1998; Yule, 1995). In other places (e.g. UK) where percentage wheel track area is greater (Chamen, 2009), and the Victorian mallee and West Australian wheat belt, where wind erosion is a high risk (Isbister et al., 2013), wheel tracks are sown. These situations demonstrate the flexibility of CTF to deal with different challenges in different places. In the vegetable industry, where compacted wheel tracks in a CTF system could reasonably be expected to comprise 30% or more of the field area, erosion on steep slopes may be an issue, particularly at the interface of the soft soil in the crop bed and the compacted soil in the wheel track. In Tasmania, the greatest proportion of the prime vegetable cropping land ranges from 13-28% slope (Cotching, et al., 2002), although slopes over 35% are also cropped (McPhee et al., 2013). Observations on more moderate slopes (<5%) showed evidence of reduced runoff and erosion under controlled traffic compared to conventional traffic, with no evidence of erosion of the wheel track or the edge of the crop bed (McPhee, unpub. data).

There is no doubt that wheel track management and maintenance can be a priority issue in CTF, both in order to maintain wheel track integrity and trafficability, and from an erosion perspective. The agricultural equipment industry has responded with the design and production of a number of wheel track renovator options (Isbister et al., 2013). Despite the challenges, wheel track erosion is a largely solvable problem, with combinations of layout, mechanised maintenance and crop cover being at the disposal at the farmer. Nevertheless, some view the challenge of erosion as being a key reason for not adopting controlled traffic (Hagny, 2005).

2.6.3 Field efficiency

A key requirement of controlled traffic is for all traffic to stay on the permanent wheel tracks. While the compacted nature of these tracks makes them an important contributor to improved timeliness and reductions in energy use, as previously outlined, they can, paradoxically, also be a detriment to field efficiency and improved timeliness on account of the traffic movement constraints they impose. This is particularly the case for materials handling operations that require in-field service from another vehicle, such as harvest chaser bins. One of the most demanding elements of implementation of controlled traffic is the need to ensure traffic always travels to the end of the field before turning out, a constraint which is not present in random traffic systems. Consequently, carrying capacity and support vehicle logistics become important determinants of field efficiency. To the extent that lower field efficiency extends the time to complete an operation, this can also affect timeliness (Bochtis et al., 2009; Wilson, 2006).

Simulation modelling and field validation of slurry application, which requires an application unit serviced by a headland-based refill unit, showed increases in transport distance of 48% and 25%, and reductions in field efficiency of 7.4% and 4.7%, in two separate fields (Bochtis et al., 2010). Their work also showed that, contrary to normal expectations, orientating wheel tracks parallel to the longest side of the field did not always lead to the most efficient travel and transport situation (Bochtis et al., 2010). The impact of controlled traffic on field efficiency is relevant primarily to operations that involve materials handling (e.g. seeding, spraying, fertiliser application and harvest), as an inevitable component of such operations is the need to refill (or unload) machinery. If this requires the primary work unit to leave the main part of the field and travel to the headlands in a controlled traffic system, it is likely the unit will spend some time travelling empty (in the case of application operations) or full (in the case of harvest), rather than performing the main function of the operation. Field efficiency can be significantly improved by servicing the primary unit with a nurse or chaser unit, although that may be an added capital cost to the operation. In situations where the use of service units is already common (e.g. haul out bins in grain and cane harvesting), the consequence of controlled traffic vehicle movement constraints is to increase the travel distance of the haul out unit, given the necessity to travel to the headland before driving to the unloading point. It has been said that one of the bigger challenges to implementation of controlled traffic in the cane industry was training haul out drivers to stay on the track (which was a smoother and faster, albeit longer, route to unload) rather than normal habit of travelling diagonally across the rows (B. Robotham, Bureau of Sugar Experiment Stations (retired), pers. com.).

2.6.4 Cropped area

One other perceived disadvantage of controlled traffic is the loss of cropped area to wheel tracks. As noted previously, this may be the case if wheel tracks are left unsown, as in some grain growing regions. In some regions, crop is grown in the wheel tracks for the purposes of erosion control, even though the yield will be lower and the crop may lag in maturity, or simply because the area of the wheel tracks is a significant portion of the field (Antille et al., 2015). Many vegetable crops are grown in rows or beds (e.g. potatoes, onions, beans). In these cases, in-season machinery straddles the crop, and the wheel tracks do not grow crop, even in conventional production systems, so the argument about loss of production area is irrelevant.

2.7 Summary of advantages and disadvantages of controlled traffic

The advantages and disadvantages of controlled traffic adoption that have been covered in the preceding sections are summarised in Table 2-2.

Table 2-2. Summary of advantages and disadvantages of adoption of controlled traffic.

Advantages *	Disadvantages *
Improved: • soil structure • biology • infiltration • soil aeration • soil water storage • internal drainage • water and fertiliser use efficiency • crop growth • yield • timeliness • root crop harvest • economics • social life	• machinery modification and replacement costs • erosion risk of compacted traffic lanes • accurate machine tracking on compacted wheel tracks • potential reduced field efficiency due to traffic constraints • loss of cropped area if wheel tracks are left bare • achieving machinery integration in situations where there is a heavy reliance on contractors
Reduced: • runoff • erosion in the cropping zone • soil borne diseases • energy use for tillage • GHG emissions • number of tillage operations • tillage equipment inventory • tractor size • capital costs • operating hours • operating costs	* Not all disadvantages will be present in all situations. Evidence suggests most advantages will be present in most situations.

2.8 The future

Very few changes to farm management systems offer such potential to improve the economic, environmental and social sustainability of crop production as the adoption of controlled traffic. The main hurdles to adoption are mindset, changing to a dimensionally integrated machinery suite (both at the individual farm level and across a number of contractors where required) and adjusting farm layout to mitigate erosion risks (Isbister et al., 2013). The mindset challenge is neither industry nor stakeholder specific. Conceptualisation of the changes required can be difficult in some industries (e.g. vegetables), not only for individual farmers, but also other industry stakeholders, such as processors, who exert considerable influence over the uptake and direction of innovations. The machinery and layout challenges differ between industries, locations and operators. Machinery changes are a significant issue in the vegetable industry. Progress in the development of wide span tractors holds promise of a platform that could be used to provide a common track gauge across a variety of machines used for different field operations (Pedersen et al., 2013). Ultimately, it is the need to manage soil compaction to ensure future soil sustainability and productivity that is important. Controlled traffic happens to be a proven method of achieving this goal.

Given the many challenges of adoption in some industries, it is prudent to consider alternatives to controlled traffic. One option for reducing soil compaction is the use of small, light-weight equipment. This would have obvious negative impacts on labour and machine productivity, so such a move is usually considered in the context of automation. This leads to the concept of light-weight 'swarms' of small machines, operated in sufficient numbers to achieve the productivity of fewer, larger machines. The concept of light-weight autonomous swarms as a 'solution' to soil compaction has received attention in recent years (Anon., 2018; Leonard, 2013). There has been very little analysis and reporting of the logistics and productivity capability of such swarms, and whether or not they are able to achieve the level of soil that has been shown through the adoption of controlled traffic. Modelling suggests it will be a very significant challenge to achieve CTF-equivalent soil structural improvement and maintain in-field productivity using light-weight autonomous swarms (McPhee et al., 2020).

2.9 Conclusion

The pathway forwards for controlled traffic in the vegetable industry is far from certain. As noted in this literature review, there are many benefits to the adoption of controlled traffic. There are also many challenges, particularly in the mixed vegetable production sector. Examples of successful adoption, outlined earlier, exist in situations where there is limited crop diversity in the rotation, limited variation in harvest machinery design, or significant use of hand harvesting. Nevertheless, even in these simplified circumstances, change can be difficult. The adoption of tractor-based permanent bed systems can require significant (and expensive) machinery changes over a short period of time to meet the needs of dimensional integration across a range of crops in the rotation (Kable, 2019).

Factors other than cost of machinery changes also influence the direction and rate of change. There are numerous stakeholders with many complex interrelationships in the mixed vegetable industry. In the Tasmanian context, and also evident in other places, these include farmers and contractors (who between them bear the majority of the costs of mechanical change) and the purchasers of commodities, such as vegetable processors and fresh market packers (McPhee & Aird, 2013). The pathway to change will require a collective vision on the part of all industry players, taking into account the desires for future sustainability and profitability, and a willingness to share both the costs and benefits of change.

CHAPTER 3. MACHINERY INTEGRATION AND LAYOUT CONSIDERATIONS IN VEGETABLE CROPPING SYSTEMS

3.1 Background

With excessive traffic and tillage being features of mechanised vegetable production, the sector is an obvious candidate for the use of controlled traffic to improve soil management and productivity. However, uptake is virtually non-existent. Reasons for uptake of any change in technology can be wide-ranging and may vary from the circumstances of the individual grower to the structure of the relevant industry. In the case of controlled traffic, the availability (or otherwise) of appropriate equipment may also be a challenge. The first paper in this chapter analyses the mechanisation landscape of the Tasmanian vegetable industry and reviews the challenges to adoption of controlled traffic in the industry.

Layout is also an important aspect in the design of controlled traffic farming systems. Layout influences field logistics and efficiencies, and also runoff and drainage, which is important in both flat landscapes with poor surface drainage, and undulating landscapes with heightened erosion risk in wheel tracks and furrows. Undulating landscapes may also feature zones of limited drainage caused by concavity of the surface profile. The second paper in this chapter uses topographical mapping to assess the importance of topography and propose options for achieving acceptable layout design, whilst concluding that topography is not necessarily a constraint to effective layout in the context of the landscape in which the Tasmanian vegetable industry operates.

The two papers that comprise Chapter 3 are:

> **McPhee, JE** and Aird, P, (2013) 'Controlled traffic for vegetable production: Part 1. Machinery challenges and options in a diversified vegetable industry', *Biosystems Engineering*, **116** (2) pp. 144-154
>
> **McPhee, JE**, Neale, T and Aird, P, (2013) 'Controlled traffic for vegetable production: Part 2. Layout considerations in a complex topography', *Biosystems Engineering*, **116** (2) pp. 171-178

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Research Paper

Controlled traffic for vegetable production: Part 1. Machinery challenges and options in a diversified vegetable industry

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Controlled traffic farming (CTF) maintains the same machinery wheel tracks in cropping fields year after year, thereby isolating the impacts of traffic compaction from the soil used for crop growth. Benefits of CTF include improved energy efficiency, soil health, crop yield, timeliness and economics.

The successful adoption of CTF in the Australian grain and cane industries has been largely based on a limited equipment suite and flat to mildly sloping topography. The Tasmanian vegetable industry faces a very different scenario, with a wide diversity of machinery, and topography ranging from gently to steeply undulating.

Two key technical challenges to the adoption of CTF in vegetable and mixed cropping were investigated – 1) working and track width compatibility of current equipment, and 2) farm layouts suited to steeply undulating topography.

Almost no machines are currently compatible with a common track or working width, although some are suitable for modification to enable CTF operation. Some harvest machinery (e.g. single row potato harvesters) provides few options for change. Seasonal CTF represents a possible starting place for adoption until more compatible machinery is available.

Findings in relation to farm layouts are reported in a companion paper (McPhee, Neale, & Aird, 2013).

1. Introduction

Controlled traffic farming (CTF) is a crop production system in which the crop zone and traffic lanes are distinctly and permanently separated. In practice it means that all implements have a particular span, or multiple of it, and all wheel tracks are confined to specific traffic lanes (Baker et al., 2006). This improves productivity (Chen et al., 2008; Li, Tullberg, & Freebairn, 2007) by eliminating compaction from the crop growth zone, and improves timeliness due to improved trafficability on permanent compacted wheel lanes (McPhee, Braunack, Garside, Reid, & Hilton, 1995b; Price, Petersen, Robotham, & Kelly, 2004).

Research over several decades has highlighted the value of controlled traffic for managing soil compaction (Dumas, Trouse, Smith, Kummer, & Gill, 1973; McHugh, Tullberg, &

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Nomenclature

GNSS	global navigation satellite systems
RTK	real time kinematic
CTF	controlled traffic farming
SCTF	seasonal controlled traffic farming
Track gauge	the centre to centre distance between tyres across a machine, perpendicular to the direction of travel

Freebairn, 2009; Taylor, 1983; Tullberg, 1994). Progress in commercial CTF adoption has been made in the Australian grain and cane industries in the past 10–15 years. Grain and cane industry experience shows CTF has significant impacts on economic, environmental and social sustainability (Bowman, 2008; Kingwell & Fuchsbichler, 2011; Loeskow, Cameron, & Callow, 2006; Tullberg, Yule, & McGarry, 2007). Economic benefits arise from improved crop yields (Chamen & Longstaff, 1995; Vermeulen & Mosquera, 2009) and lower operating and capital costs due to reduced fuel use and lower tractor power requirements (McPhee, Braunack, Garside, Reid, & Hilton, 1995a; Tullberg, 2000). Environmental benefits arise from improved soil structure and soil–water relations (McHugh et al., 2009; Qingjie et al., 2009) and improvements to growers' lifestyles have been noted by Tullberg et al. (2007).

There are few examples of fully integrated controlled traffic in the vegetable industry, and those that do exist are mostly in situations with simple crop rotations and machinery requirements. Vegetable production systems commonly feature excessive wheel traffic and tillage, which contribute to soil degradation and require high energy inputs. This is very much the case in the Tasmanian vegetable industry.

Potential benefits of CTF for the vegetable industry can be inferred from research and commercial adoption in other industries, such as grain and cane. These include:

- Machinery – reduced tillage, with possible adoption of no-till techniques; reduced fuel use and tractor time; lower capital investment in tractors and tillage equipment (Lamers, Perdok, Lumkes, & Klooster, 1986; McPhee et al., 1995a).
- Soil and water – improved soil structure, biology, infiltration, water holding capacity and drainage, and reduced run-off and erosion (Bai et al., 2009; Boulal, Gomez-Macpherson, Gomez, & Mateos, 2011; Braunack & McGarry, 2006; McHugh et al., 2009; Radford, Yule, McGarry, & Playford, 2007).
- Crop – higher, more uniform yield; improved crop quality and more even maturity (Chen et al., 2008; Dickson, Campbell, & Ritchie, 1992).
- Farming system – improved timeliness; fewer clods in root crop harvest leading to reduced harvest costs; adoption of minimal or no-till techniques; capacity to band spray or inter-row drill crops using guidance; more effective application of precision farming techniques such as yield mapping and variable application of inputs (Bramley, 2009; Dickson et al., 1992; McPhee et al., 1995b; Radford & Yule, 1996).

Although the potential benefits are numerous, implementation of CTF in the vegetable industry has many challenges. Two essential elements required for an efficient and effective CTF system are:

- all equipment must have a common wheel track gauge, or multiple of it, with compatible working widths (Baker et al., 2006)
- farm planning must incorporate changes in tillage and traffic practices into the management of erosion, drainage, and field logistics (Tullberg et al., 2007).

These issues tend to be particularly challenging in the vegetable industry on account of machinery diversity and the difficulty of modifying machinery, particularly, for example, root crop harvesters. It is estimated that approximately 60 vegetable, arable and mixed cropping farmers in Europe (The Netherlands, Denmark, Sweden, UK) have implemented partial CTF systems (H Pedersen, Director, CTF Europe.dk, Denmark, pers. comm.), but progress towards a fully integrated system is hindered by a lack of compatible harvest machinery to cater for the range of crops grown. In these cases, the system used has become known as seasonal CTF (SCTF) (Vermeulen, Mosquera, Wel, Klooster, & Steenhuizen, 2007). In SCTF, the focus is to achieve machinery integration for tillage and crop management operations, but given the lack of compatible harvest equipment, the randomness of harvest traffic is accepted. With satellite guidance and accurate farm maps, the operator is able to return to the same wheel track locations for tillage operations following harvest. Although the soil benefits achieved with SCTF are less than with a fully integrated system, research has shown a number of benefits accrue, despite the regular return of random harvest traffic (Vermeulen & Mosquera, 2009).

The Tasmanian vegetable industry has a number of similarities to the European situation, in that a diversity of crops is grown (e.g. potatoes, onions, carrots, broccoli, cauliflower, peas, beans). Some non-vegetable crops are included in the rotation (e.g. pyrethrum, poppies, cereals). Tasmania has a cool temperate production environment, with a winter dominant rainfall, and most cropping occurring in the summer, although some crops are grown over winter for summer harvest.

A range of machinery configurations is used in the industry, particularly harvesters. There is currently no commonality of track gauge or working widths between harvest equipment used in the industry. Many operations, particularly harvest, but increasingly tillage, seeding and spraying, are contractor-based. While contractors present an opportunity for rapid adoption of new technologies, issues surrounding machinery ownership impact on the ease of change. While the main expenditure on equipment modification would need to be made by contractors, the major benefits of CTF accrue to growers and the environment. Sharing the costs and benefits of such changes, which have significant industry-wide potential, needs consideration. Another factor impacting on adoption is land ownership, with increasing use of leased land for production, and consequent shorter term views on issues of soil management.

Successful implementation of CTF requires a systems approach to farm planning, field logistics, drainage and erosion management, and machinery replacement (Tullberg et al., 2007). Direct monetary costs include machinery modifications, the purchase of guidance technology and possibly changes to farm layout.

Two significant technical challenges to the implementation of CTF for vegetable production in Tasmania were investigated:

- machinery configurations required for successful implementation of CTF
- farm layout design for CTF in steeply undulating topography

Within the machinery context, this paper reports on:

- a survey of track gauge, tyre section width and working width dimensions of machinery currently used in the Tasmanian vegetable industry
- investigation of the feasibility of equipment changes (particularly harvesters) needed to implement CTF
- machinery configuration issues that mitigate against CTF adoption
- proposals for both incremental and transformational approaches and technologies that could facilitate the adoption of CTF

Farm layout issues related to representative Tasmanian vegetable farms are covered in a companion paper (McPhee, Neale, & Aird, 2013).

While the focus of this work was the Tasmanian vegetable industry, the principles are relevant to any industry which grows a diversity of crops and uses a range of equipment with dimensions that are currently incompatible with the objectives of controlled traffic.

2. Materials and methods

2.1. Vegetable industry machinery survey

An audit was done of current vegetable industry equipment, allowing exploration of possible pathways to the adoption of CTF. Details on machinery widely used in the industry by individual growers and contractors (e.g. tractors, tillage equipment, grain and potato harvesters) were obtained from suppliers' catalogues. In the case of tractors from global manufacturers, catalogues with technical specifications were obtained from all major suppliers in the region, representing all but a very small percentage of the brands sold in Tasmania. As there is no locally-based (i.e. Australian) tractor manufacturing industry, and all tractors reviewed were imported from Europe or the USA, it is reasonable to assume the dimensional information is consistent with tractors available from the same manufacturers in other parts of the world. A similar catalogue-based survey approach was taken for commonly used tillage and harvesting equipment, such as rotary hoes, power harrows and grain and potato harvesters. Dimensional details, such as tyre sizes, track gauges and working width, of specialised machinery, which tends to be represented by a limited number of examples (less than 10 of each type) in the Tasmanian industry (e.g. pea, bean and carrot harvesters) were obtained through measurement.

As part of the survey, which was completed in 2009, catalogue data on track gauge adjustability were collated for a total of 88 tractors in the 40–180 kW range. An assessment was made of the number of tractors that could easily be adjusted to 2.0 m and 2.2 m track widths, without exceeding warranty conditions. These track gauges were selected because:

- there is some interest in the vegetable industry in changing to a 2 m track gauge, and based on twin-row potato harvester dimensions, 2 m is a more practical bed width for root crops under controlled traffic than the current 1.625 m
- a number of implements are manufactured in 1 m increments, making a 2 m track width suitable for 2, 4 or 6 m equipment
- a 2.2 m track width would minimise track gauge changes on some harvesting equipment (e.g. some bean and root crop harvesters)

A similar survey was repeated in 2011, in response to potato industry interest in a controlled traffic system based on a 2.5 m track gauge, which would allow a tractor to straddle 3 rows of potatoes on current planting configurations. The more recent survey covered 160 tractors in the power range 40–265 kW. The expanded range is a reflection of changes in the Tasmanian market towards larger tractors for increased work rates, although 75% of the tractors included were still in the 50–150 kW range, which is also reflective of the market distribution.

Key tillage implements were surveyed to identify changes required for their use in a controlled traffic system. The implements of most interest were deep rippers, power harrows, rotary hoes and reversible ploughs.

3. Results

3.1. Vegetable industry machinery survey

3.1.1. Machinery configurations

About 11 crops are regularly grown within the Tasmanian vegetable industry, of which seven are vegetables. The remainder include pastures, cereals, pyrethrum and poppies, the latter two being economically important crops which do not occur in combination with vegetable crops in any other mechanised cropping system in the world. The integration of row crops (most vegetable crops) and broadacre crops makes the adoption of CTF more challenging than if only vegetables or cereals were grown. Some 17 different types of harvest machinery are used, with as many as 25 different tyre and track gauge configurations. The lack of compatibility between track gauges, working widths, and commonly used tyre section widths is indicated in Table 1.

Although a wide range of crops are grown, the dominant vegetable crop in Tasmania is potatoes. The most common tractor track gauge used for in-crop work is dictated by the requirements of potatoes, some 90% of which are grown on row spaces of 864 mm (34″), the remaining 10% being on

Table 1 – Track gauges, tyre and working widths of machinery used in the Tasmanian vegetable industry.

Equipment	Track gauge (mm)	Tyre section width (mm)	Working width (mm)
Tractors	1625, 1730, 1830	350–600	
Single row potato, carrot, onion harvesters	2000–2500	300–600	800–900
Tricycle carrot, potato, onion harvesters	1100–2600	600–750	750–1600
Pea, bean harvesters	2200–2600	400–750	2950–3330
Cereal, pyrethrum, poppy harvesters	3000–3300	300–800	4550–8000

813 mm (32″) (P. Hardman, Simplot Australia P/L, pers. comm.). Therefore, the most common track gauge is 1.73 m, with a small percentage on 1.625 m. Local dealers advise that the vast majority of tractors are delivered ex-showroom with a track gauge of 1.73 m. Tractors used for primary tillage may have wider track gauges, as, in the absence of controlled traffic considerations, there is no need to match with the narrower gauge. Because of the dominance of potatoes in the cropping rotation, most other vegetable crops are grown in rows or beds based on one of those track widths, although there has been a recent trend in the fresh market sector to a 2 m track gauge for productivity reasons. While CTF was not a major consideration in this change, some operators now see a synergy between the move to 2 m and the potential for CTF.

3.1.2. *Tractors*

The audit of tractor dimensions revealed that half of the tractors surveyed could be adjusted to 2.0 m track gauge, and 7% to 2.2 m, whilst staying within warranty limits. If very simple additional measures were considered, such as spacer plates not exceeding 50 mm, 61% could achieve 2.0 m, and 22%, 2.2 m. In the power range of interest in the vegetable industry at the time of the original survey (up to 180 kW), very few tractors could achieve a track gauge greater than 2.2 m within the manufacturer's warranty. It was clear that track gauges over 2.2 m would be difficult to achieve without special warranty conditions, or specialist retro-fit modifications. The more recent survey indicated 64% of tractors surveyed were capable of 2 m track gauge within manufacturer's specifications, and 34% were capable of 2.5 m. Tractors capable of 2 m track gauge were concentrated in the 50–150 kW range, while those capable of 2.5 m track gauge were reasonably evenly spread over the range from 50 to 265 kW.

3.1.3. *Tillage equipment*

Rippers with working widths of 3–6 m are widely used in the industry, with 3–4 m being most common. These are relatively easy to adjust for controlled traffic operation. Retention of compacted wheel tracks can be achieved by removing or repositioning tines that track immediately behind the tractor tyres. With reductions in implement draft due to the separation of traffic from the crop bed, and the exclusion of wheel tracks from the tillage operation, it would generally be possible to extend the implement frame to achieve a CTF compatible working width, if required.

Power harrows and rotary hoes are generally available from 1.2 to 2.1 m widths in 0.3 m increments, 2.5–5.0 m widths in 0.5 m increments and 6–8 m in 1 m increments. Neither are ideal implements for use in CTF, but relatively minor adjustments can be made to allow them to fit the system. The retention of compacted wheel tracks could be achieved by removing the tines or blades that track in line with the tractor tyres, although it has been observed that it is uncommon for a single rotor on a power harrow to align with the tractor wheel tracks. This makes it more difficult to effect a simple modification to retain wheel tracks, such as removal of the tines from one rotor.

Reversible ploughs are basically unsuited for use in a CTF system because they shift soil sideways during operation, and are incompatible with the objective of retaining defined separation between wheel tracks and crop growth zones.

3.1.4. *Planting and seeding equipment*

Potato planters are most commonly 2 or 4 row. Adjustments in row spacing of approximately 100 mm cater for the commonly used row spacings of 810 and 860 mm. The adoption of a 2 m track gauge by some producers has led to limited use of 3-row bed systems for fresh market potatoes, although there has been no such move in the processing sector. However, it does suggest that a 2 m CTF system may provide opportunities for alternative planting configurations.

Precision seeders are used for sowing carrots, onions and beans, and generally have some degree of adjustability of row spacing. Modification to these machines is unlikely to be a significant barrier to CTF adoption, and any changes required to match the needs of CTF would be relatively simple.

3.1.5. *Harvesters*

3.1.5.1. *Potatoes*. The most common potato harvester in Tasmania is the offset single row bunker design, which has an offset tyre arrangement to account for the load of the bunker. While some harvesters allow track gauge adjustment, it is not just track gauge that is relevant, but also tyre location to maintain stability. For track gauges less than 2.5 m, this type of harvester is very difficult to modify to match tractor track gauge and still maintain stability. Even if the track gauge was modified to match a tractor on 2.5 m, the single row digging front necessitates traffic passes 810 or 860 mm apart, resulting in a high percentage of compacted land area. Twin or three row harvesters offer better prospects for integration into a CTF system, although modifications would still be required to achieve the dual requirements of matched track gauge and machine stability.

3.1.5.2. *Onions*. Onion harvest may use lifters, toppers and harvesters, depending on requirements. Lifters are relatively simple machines with little scope for modification. A changed bed width would require new lifters built to the appropriate dimension. Toppers are sometimes used as part of a windrow turning process in Tasmania, or they may be incorporated into the harvester. The impacts of changes in bed width will be much the same for toppers as they are for harvesters. Onion harvesters take various forms with a diversity of tyre arrangements. Single row potato harvesters are used with onion pick-up fronts, and these face the same modification constraints described previously for potato harvesters. Others are single and twin-bed centre pull machines with four or six tyres under the rear of the machine. These have capacity for track gauge adjustment through extension of the sub-frame and re-positioning of wheel brackets. Two important changes would be required for controlled traffic:

- conversion to two tyres to carry the same load as the existing four or six. As vertical space is limited under such machines, the greater load bearing capacity required of fewer tyres would need to be met with wider tyres. While this may appear counter to the aim of controlled traffic to minimise the width of the compacted track, tyre combinations are available which would provide the necessary load bearing capacity within the width of most rear tractor tyres, and therefore not cause a wider track print. These options are easier to accommodate on the smaller harvester with four tyres.
- addition of weights to balance the offset discharge conveyor. For this type of harvester, there is no easy way to modify the discharge conveyor to address the offset load.

Such changes would be possible without compromising the operation of the harvester.

3.1.5.3. *Carrots*. Three types of top-pull carrot harvester are used in the Tasmanian fresh market vegetable sector. Three point linkage top-pull carrot harvesters are generally light machines, although some models have load bearing wheels that support the machine when in operation. There are limited options for track gauge adjustability, although modifications to allow side-shift of the picking head are possible. Trailed single and twin row harvesters have similar tyre and axle arrangements as single row potato harvesters, so face similar modification constraints. Self-propelled tricycle style harvesters (Fig. 1) are basically unsuited for use in CTF operations. None of the carrot harvesters currently used in Tasmania lend themselves to easy incorporation into a CTF system. Current fresh market carrot sowing configurations vary considerably. Examples include:

- 1.6 m track gauge – twin or triple rows on ridges with 800 mm centres between ridges
- 1.8 m track gauge – 4 pairs of rows 80 mm apart with 375 mm centres between pairs
- 2.1 m track gauge – 4 pairs of rows on a bed with 525 mm between pairs

The arrangements are configured to suit the intake capacity and head separation spacing of top-pull carrot harvesters. Double head top-pull harvesters are best suited to rows 300 mm apart. Consecutive passes of a carrot harvester will occur anywhere between 375 and 1050 mm, depending on the sowing configuration and the harvester used. Combined with tyre widths of 300–600 mm, this inevitably means a high percentage of wheel track area, calculated at 75–100%.

Fig. 1 – Front (a) and rear (b) views of tri-cycle carrot harvester showing wheel arrangements that are incompatible with CTF.

Processing carrots are dug with bottom-lift twin row diggers. These have a working width of one bed, which is currently 1625 mm, but alternative models of similar design could be used for wider beds that might occur within a controlled traffic system. Although the digging width can't be modified, and so must be selected with the bed width in mind, the wheel and axle configurations could be modified to achieve compatible track gauges.

3.1.5.4. *Peas*. The most widely used pea viner in the Tasmanian industry has a track gauge of 2.53 m. There is no capacity for the track gauge to be reduced. Because pea viners have a considerable amount of fore-aft and side-to-side adjustability as part of their levelling system, there is little opportunity to use taller tyres. Reversal of the wheel rims on currently used models could extend the track width to a maximum of 2.97 m.

The working width of currently used pea viners is 3.33 m, with little option for easy modification to either a narrower or wider picking width. Any track gauge chosen for use in the Tasmanian vegetable industry would require a different working width for the pea viner to maintain operational efficiencies. One of the major drawbacks of peas is the requirement of the viner to operate across the fall of the crop to ensure optimum recovery, which may not coincide with the direction of a CTF layout.

3.1.5.5. *Beans*. French beans are grown in Tasmania for both the processing and fresh market sectors. Track gauges for the two types of bean harvester used in the industry are 2.1–2.2 m, with little capacity to reduce the track gauge due to clearance limitations. It would be possible to gain small increases in track gauge through the use of spacers. There is no room to fit taller tyres to either type of bean harvester because of space limitations imposed by the cab. Working widths range from 2.95 to 3.05 m. Modification of the picking front would be a major undertaking, and the only way to match working width to a track gauge less than 3 m would be to operate using a partial cut on each pass. This approach has been taken in 2 m controlled traffic trials to maintain traffic on existing compacted wheel tracks, but with a loss of harvest efficiency, which is not a proposition for commercial operation.

3.1.5.6. *Pyrethrum*. Pyrethrum is a short-term perennial crop, harvested two to four times over its life. It is an important part of the cropping economy in Tasmania, and also serves as a break crop in the vegetable rotation. Its harvest mechanisation is closely related to grain production. The harvest process involves windrowing the crop when flowers are at optimum maturity. The windrows dry in the field for a period of up to three weeks, dependent on weather, before recovery with a windrow pick up front on a grain harvester.

Two types of windrower are used. The dominant type has a track gauge of 3.02 m and a cutting width of 4.55 m, although the operational width is generally less to account for crop which has lain over. The other type is tractor-based, with a similar width cutting front, and a normal track gauge for tractors, which is approximately 2.3 m for those used. Grain harvesters used for windrow recovery have a standard harvester track gauge of approximately 3 m.

3.1.5.7. *Grain*. Cereals are often grown as a rotational break crop and to provide organic matter for soil benefits. There is considerable experience in modifying grain harvesters to suit 3 m CTF systems in other parts of Australia. Since grain harvesters are supplied ex-factory on 3.02 m track centres, the most common changes required are to the cutting front, to match the working width of other equipment, and the outloading auger, to ensure compatibility with chaser bin location on the CTF wheel tracks. The cutting platform widths of grain harvesters used in Tasmania range up to 8 m. Chaser bins are not used for grain harvest in Tasmania.

3.1.5.8. *Poppies*. Two dominant types of poppy harvester are used in the Tasmanian industry. One has the cutting front mounted on a reversible tractor with a trailed collection bin. The track gauge of these can be matched to whatever is possible for the particular tractor, which will generally be 2–2.5 m. Current models are 2.3 m with 710 mm section width tyres. The other type of harvester has similar dimensions to grain harvesters, namely 3 m track gauge with 700–800 wide tyres, and a variety of cutting front widths.

4. Discussion

An integrated CTF system requires machinery working widths to be a multiple of the track gauge in order to maintain operational efficiencies and allow matching of track locations. This is a relatively simple change for some machines (e.g. sprayers), but not for many vegetable harvesters.

An inevitable question in the adoption of CTF concerns choice of track gauge. Controlled traffic is not fundamentally about a specific track gauge. It is about minimising the area of soil compacted by machine traffic and isolating it into permanent traffic lanes. The most appropriate track gauge to choose is the one that meets that objective in the simplest fashion, although the general goal is to make the track gauge as wide as is practicably possible. A 3 m standard has evolved in the Australian grain industry because harvesters are supplied ex-factory with a track gauge of 3 m, or very close to it (Vermeulen, Tullberg, & Chamen, 2010). As this is the most difficult machine to modify, it is easier to modify other equipment to suit. The vegetable industry situation is not so clear cut.

Extending axles may be a simple way to change track gauge on tractors and some harvesters, but many factors have to be considered. This may be done by reversal of asymmetrical wheel rims, or the addition of spacers, provided loads on axles and bearings are maintained within safe limits, and steering mechanisms still function.

Logistical considerations also factor in track width decisions. Even if every machine could change to suit a common track gauge, operators would be reluctant to change if the resultant widths imposed additional limitations on public road transport. Given the widespread use of contractors in the industry, and the regular use of public roads for travel and transport, legal considerations are important. In keeping with Tasmanian legislation, it is necessary to keep total machine width under 3.5 m for unrestricted road travel, or under 3.2 m for transportation by truck (*Tasmanian Legislation – Vehicle and Traffic (Vehicle Operations)*, 2010). Similar constraints exist in most countries, particularly in closely settled areas.

4.1. *Track gauge options for CTF*

The diversity of equipment used in the Tasmanian vegetable industry does not lead to an obvious choice for the most appropriate CTF track gauge. Adoption of controlled traffic would require major changes for almost all vegetable harvesting equipment used in the industry. Consideration is given here to three options which could help address the integration of vegetable and cereal operations in the Tasmanian context:

- 1.7 m/3.4 m, with vegetables grown on the 1.7 m system, and cereals, pyrethrum and poppies on 3.4 m
- 3 m for all crops
- A hybrid system using a narrower track gauge for vegetables and all tractors, and a wider track gauge for cereal harvesters. Options include 2 or 2.5 m for vegetables and a straddling 3 m track gauge for cereals, pyrethrum and poppies.

4.1.1. 1.7 m/3.4 m

The option of mixing track gauges on a 1:2 ratio has attractions for growing a mix of row crop vegetables and broadacre crops. The larger dimension, being twice the smaller, is suited to cereal harvest equipment with minor modification to achieve a 3.4 m track gauge. Although pea and bean harvesters don't currently match other equipment, and any modification is seen as a major undertaking, a track gauge close to 3 m may be achievable. The smaller dimension (1.7 m) is possible for many tractors, but would still require significant change from current practice in the style of some harvesters – e.g. potato, onion and carrot harvesters. The disadvantages of the narrower track gauge are:

- a high percentage of land area devoted to wheel tracks, 50–60%, depending on tyre sizes used
- the risk of machine instability for larger tractors and harvesters
- recent observations indicate that harvesting root vegetables from a 1.7 m controlled traffic bed is difficult with current twin row harvesters, due to the encroachment of wheel track compaction into the crop bed.

4.1.2. 3 m

Few 3 m track gauge tractors are available ex-factory, and only in power ranges over 130 kW. Australian manufactured after-market 3 m modifications are available for larger tractors, but experience with this change in smaller tractors (less than 100 kW) is limited to a few isolated European examples, with varying experiences in reliability.

The dominant styles of potato, onion and carrot harvester imported for use in the Tasmanian industry do not suit 3 m. Some European machines, such as 3-row potato harvesters, could be modified to suit a 3 m track gauge. However, machines suited to a 3 m track gauge will inevitably be larger than those required for a 2 m system, leading to increases in weight, length, power requirements and cost. Furthermore, a change to this type of harvest technology would require a fundamental change to the logistics and supporting infrastructure for potato harvest. This is certainly not impossible, but this demonstrates how decisions about controlled traffic adoption are not just about soil management, but have flow on impacts to operational aspects of the industry.

Grain harvesters are currently manufactured with a 3 m track width, as are some pyrethrum windrowers. To suit a 3 m system, the cutting width of windrowers would need changing to either 3 m, which would impact operational efficiency, or 6 m, which would increase the windrow volume and influence crop drying rates.

Pea and bean harvesters face the limitations previously mentioned, although a 3 m track width, and matching picking front width, is probably more achievable than any other option. Most machines on 3 m track width would be just less than 3.5 m overall width, the legal limit for non-escorted vehicles on public roads. However, such vehicles would still present safety issues on narrow rural roads.

4.1.3. 2 m (2.5 m)/3 m

Another option for controlled traffic in Tasmania is the use of a hybrid system, based on 2 m or 2.5 m for vegetable crops and 3 m for broadacre crops, with the wider track gauge straddling the narrower. While current trends in the Tasmanian industry are to a 2 m track gauge for fresh vegetables, 2.5 m is of interest to the processing potato industry. Either option would work for a hybrid system. Careful selection of working widths for machinery can minimise the apparent incompatibility of such combinations (Vermeulen et al., 2010). One possible combination, based on 2 m and 3 m, using a 6 m front for grain harvest, is shown in Fig. 2. Compaction impacts of the wider footprint could be addressed with strategic tillage operations outside the narrower wheel tracks when preparing for vegetables.

4.1.4. Comparing options

All track gauge options have advantages and disadvantages. Mechanically, the 1.7 m/3.4 m option is the easiest, but the high percentage of land area devoted to wheel tracks (50–60%, depending on tyre sizes used) is a major drawback.

The 3 m system offers the greatest combination of advantages in terms of minimising wheel track area (25%, dependent only on the widest section tyre used), improved stability and the potential for a fully integrated CTF system. Pea and bean harvesters, difficult machines to fit into any system, are more likely to fit the 3 m system than any other option. One drawback is the lack of top-pull carrot harvesters capable of operating on this track gauge. Potato harvesters that could be modified to a 3 m track width and a 2.7 m cropping bed width are available from European manufacturers. Such a change to potato harvest equipment would require major changes to the infrastructure and logistics of potato harvest compared to the system currently used in Tasmania. Equally important is the off-farm issue of safe travel on narrow rural roads. While there are many movements of large machines during the harvest season, a 3 m CTF system would lead to year-round movement of wide vehicles, and increase the need for escort vehicles, with flow-on financial effects for growers and contractors.

The hybrid option is attractive in its relative simplicity for change. All cereal and similar crops would suit the 3 m option, while most vegetables could be arranged to suit the narrower track of 2 or 2.5 m. Pea and bean harvesters could also fit with minimal modification to track gauge, as their tracks would largely fit within the broader footprint of the combined narrow and wider track gauges.

Such a system may be a reasonable option for the vegetable industry, at least until there is a more compatibility in machinery design. Although the tracked area for a hybrid system is relatively high (approximately 50%, dependent on the widest tyre), it is still an improvement on normal vegetable industry practice, in which almost 100% of the field receives at least one wheeling per season, with many areas receiving more. A significant portion of the 3 m traffic would occur during summer pyrethrum or poppy harvest, when soil conditions are dryer. While this does not totally avoid soil damage, it would be minimised in comparison to the wetter conditions of autumn or winter. A summary of key points related to machinery dimensions is provided in Table 2.

4.2. Tyre selection

As agricultural machines have increased in size, use of lower pressure, wide section tyres has increased. Heavy machines

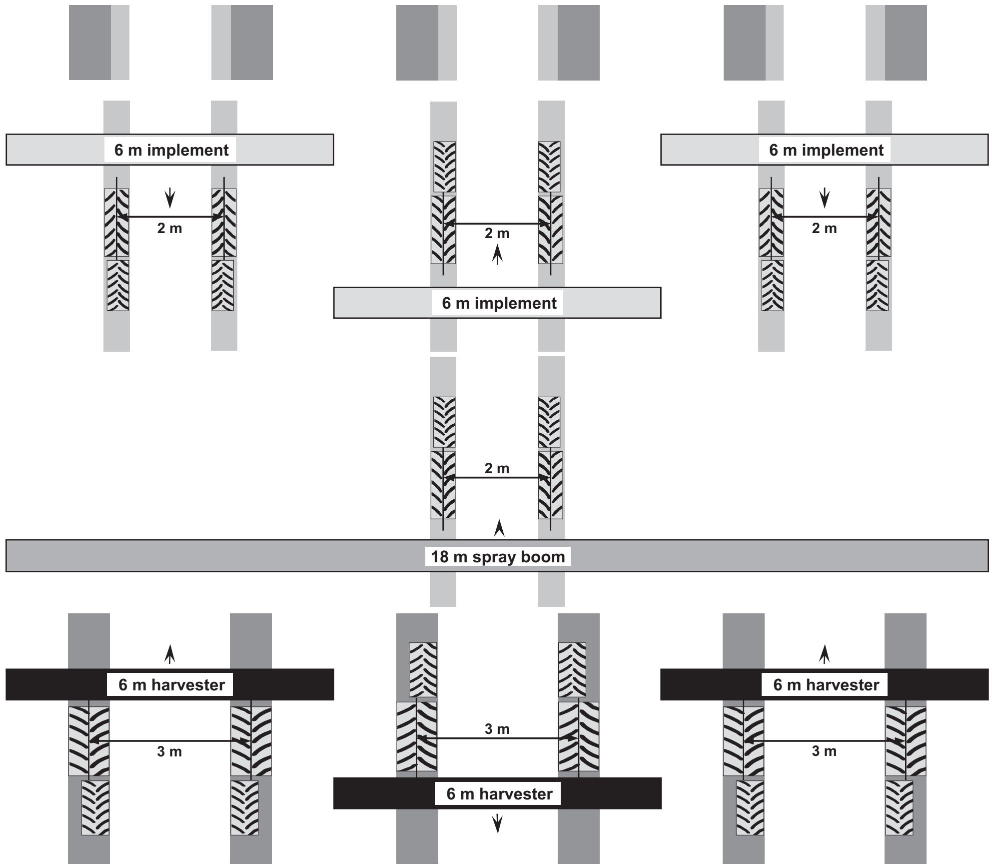

Fig. 2 – Possible integration of 2 m and 3 m track width equipment to accommodate vegetables and cereals in a controlled traffic system (after Vermuelen et al., 2010).

using these tyres still cause soil compaction below the tillage zone, and wider tyres are generally incompatible with CTF vegetable production because of the land area they impact. Another function of low pressure, wider tyres is to act as a suspension system for the machine and the operator.

Harvesters usually have the widest tyres of any machine used, with section widths up to 800 mm being common. CTF may require consideration of narrower tyres, which may need to be larger in diameter to provide adequate load capacity with reduced ground pressure (Ansorge & Godwin, 2007).

Table 2 – Comparison of current track gauges and working widths of machinery used in the Tasmanian vegetable industry, and requirements for CTF

Equipment	Current Track gauge (mm)	Current working width (mm)	Track gauge required for CTF (mm)	Working width required for CTF (mm)	Comment
Tractors	1625, 1730, 1830		2000 or 2500		Achievable for many tractor sizes used in the industry
Single row potato, carrot, onion harvesters	2000–2500	800–900	2000 or 2500	1800 or 2400 digging width	Not possible with current single row harvesters. Some multi-row harvesters available for potatoes, carrots and onions from European or US manufacturers, but still require significant change to fit CTF system.
Tricycle carrot, potato, onion harvesters	1100–2600	750–1600	2000 or 2500	1800 or 2400 digging width	Limited range of harvesters available for some crops, still require modification
Pea, bean harvesters	2200–2600	2950–3330	2500 or 3000	3000	Could fit a hybrid system
Cereal, pyrethrum, poppy harvesters	3000–3300	4550–8000	3000	Multiple of 3000	Achievable with modification

Industrially rated tyres operating at higher inflation pressures may be an option, although this has implications for machine suspension and operator comfort. Space to accommodate taller tyres is also a consideration for modification options, as many of the large tyres used are located under cabin platforms (e.g. bean, grain harvesters) with reduced capacity to fit a taller tyre. The use of rubber tracks, as has become more common for grain harvesters in Europe, may offer alternatives for some machines and would reduce the width of the contact area and the vertical space requirements. It may be possible to reduce the track gauge with the use of rubber tracks, which would help reduce the overlap between tractor and harvester track gauges in the hybrid systems suggested previously. Such a change could assist in reducing tracked area in the Tasmanian industry, where the current 3 m track gauge of grain and poppy harvesters is generally the widest critical dimension.

4.3. *Tillage equipment*

A fully integrated CTF system should significantly reduce the number of tillage operations used in vegetable production. With compaction managed by controlled traffic, and soil conditions becoming more suitable for approaches such as no-till, it is likely that only minimal tillage would be required.

The need for deep rippers should diminish, and maybe disappear, with the implementation of a fully integrated CTF system. However, during transition to a full CTF system, there would still be a need for such implements. Even in a fully established CTF system, it may be necessary to conduct remedial ripping at the interface between tracks and the crop bed.

4.4. *Transitioning to CTF*

It is clear from the survey that the adoption of a fully integrated CTF system in a diverse vegetable industry faces many challenges, particularly in relation to compatibility of machinery. GNSS RTK (Global Navigation Satellite Systems Real Time Kinematic) guidance, an essential enabling technology for any CTF system, and simple modifications to some machinery, makes it possible to implement a seasonal controlled traffic farming (SCTF) system as a transitional step.

In SCTF, the aim is to ensure that all traffic, except incompatible harvest traffic, returns to the same wheel tracks during the growing season, and after harvest. Even if the whole field is compacted by harvest traffic, with guidance, tractors can return to the same wheel track locations for subsequent tillage operations. In that way, wheel tracks can be kept while the soil between can be cultivated. SCTF has been used in Europe for some years (Vermeulen et al., 2007). In that system, it is normal that the first operation after harvest is full tillage, and wheel tracks are re-instated in permanent locations for subsequent operations.

Depending on the implements used, such an arrangement can be put in place at the time of primary tillage after harvest. For example, if primary tillage is done with a ripper, tines that follow the tractor wheels can be removed to reduce energy input while maintaining the wheel tracks. Other implements (e.g. rotary harrows) can be similarly modified by removing tines that match with the tractor wheel tracks. With relatively simple modifications, it is possible to ensure that all wheel traffic associated with pre-season tillage and in-season crop management remains in the same wheel tracks up until the point of harvest.

4.5. *The role of the agricultural machinery industry*

It is clear that current design approaches within the agricultural machinery industry do not facilitate the uptake of Controlled Traffic Farming (CTF), particularly in diverse cropping industries. A key step forwards would be agreement amongst manufacturers on standards for track gauges and operating widths (Tullberg, 2010). Such standardisation may allow alternative crop row configurations suited to providing better agronomic results, since mechanical considerations often dictate compromise in current crop spatial arrangements. The reduction in draft requirements that comes with a fully integrated CTF system (Dickson & Ritchie, 1996; McPhee et al., 1995a; Tullberg, 2000) suggests that machinery could be designed to be lighter, thereby saving materials in manufacture.

Given the diversity of equipment used in the vegetable industry, the implementation of controlled traffic would be greatly aided by the use of wide span gantry technology, a concept first recorded in the literature over 150 years ago (Halkett, 1858), and which has been the subject of research and commercialisation attempts at various times over the past three decades (Beard, McClendon, & Manor, 1995; Chamen, Dowler, Leede, & Longstaff, 1994; Hilton, 1986; Hood, Williamson, Garrett, & Young, 1987). While it is recognised there are many barriers to overcome (e.g. implement integration, road transport) before wide span technology is mature enough to be a readily available solution, the extensive modifications required to existing machinery to achieve controlled traffic compatibility for vegetables suggest the challenges of wide span adoption might not be any more difficult.

4.6. *Initial steps for vegetable industry adoption of CTF*

Implementation of SCTF would be a valuable starting point for the Tasmanian vegetable industry. While this system ignores the impact of harvest traffic, the retention of compacted wheel tracks in a constant location is a useful step forwards. The retained wheel tracks will provide benefits for traction and reduced energy use, and the amount of soil damage in the crop growth zone will at least be limited to harvest traffic. Adoption of SCTF is also likely to encourage operators to look for more compatible machinery options when replacing harvesters.

The key steps to take are:

- invest in GNSS RTK guidance, which provides operational benefits apart from SCTF, and,
- adopt a common track gauge and modular implement widths.

The use of satellite guidance is increasing, and the adoption of 2 m wheel track widths by some operators provides a basis for moving forwards. However, there is still no firm agreement within the Tasmanian vegetable industry on a track gauge standard, as evidenced by recent interest from the potato industry in a 2.5 m standard, while the bulk of the industry remains on 1.7 m. When (or if) a standard is agreed, growers and contractors would be able to either modify, or purchase new at the time of upgrade, equipment in appropriate multiples of the standard track gauge. In conjunction with guidance, this would enable an easy transition to SCTF.

A further development would be to adopt a hybrid track gauge system, such as the 2 m or 2.5 m/3 m system described previously. This would minimise the number of difficult modifications surrounding inclusion of large, incompatible harvesters.

There is significant potential for the processing and fresh packing sectors of the Tasmanian industry to play an important role in transitioning to CTF. Companies in this sector dictate or control many of the large machinery operations in the industry, such as harvest, in many cases owning the machinery. While the implementation of controlled traffic is much more than matching machinery dimensions, choosing controlled traffic compatible specifications at the time of machine replacement would at least facilitate change.

5. Conclusion

Two key machinery issues need to be addressed for the Tasmanian vegetable industry to make progress in the adoption of SCTF or CTF – track gauge and working width. The current diversity of machine styles, tyre arrangements, working widths and tyre sizes is incompatible with CTF. While there is scope for modification of some machines, a number of key machines that currently dominant in the industry (e.g. single row potato harvesters and tricycle carrot harvesters) are difficult to modify. Standardisation of track gauge and working width are central to the development of a fully integrated CTF system. The agricultural machinery industry has a key role to play in achieving standardisation.

In the absence of readily available standardised machinery, implementing SCTF would be a valuable starting point for the Tasmanian vegetable industry. Although SCTF ignores the impact of harvest traffic, the retention of defined wheel track zones would still be a useful step forwards. A further improvement would be the adoption of a hybrid system, with a narrower track gauge of 2 m or 2.5 m and a wider track gauge of 3 m, which could accommodate most of the equipment diversity in the industry. A fully integrated CTF system, based on a common track width and appropriate working width modules, will require considerable change in the agricultural machinery manufacturing sector.

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Research Paper

Controlled traffic for vegetable production: Part 2. Layout considerations in a complex topography

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Controlled traffic farming (CTF) maintains the same machinery wheel tracks in cropping fields year after year, thereby isolating the impacts of traffic compaction from the soil used for crop growth. The benefits of CTF include reduced energy use, improved soil health and crop yield, better timeliness of field operations and improved economics.

The simplest adoption of CTF occurs in flat landscapes, and mildly sloping landscapes are an advantage in relation to surface drainage. The adoption of CTF in the Australian grain and cane industries has, to a large extent, been in flat to mildly sloping topographies. The Tasmanian vegetable industry faces a very different scenario, with topographies ranging from very flat, which present potential drainage issues, to steeply undulating, which present machine tracking and erosion challenges.

Two significant challenges to the adoption of CTF in a vegetable and mixed cropping based industry were investigated – (1) working and track width compatibility of current equipment, and (2) farm layouts suited to steeply undulating topography.

Farm layout can dictate success or failure in the adoption of CTF, with the risk of concentrated runoff and consequent erosion in wheel tracks. Mapping of representative farms in north-west Tasmania showed effective CTF layouts are possible, despite undulating topography and infrastructure challenges. The direction of run for many fields is already close to that required for CTF.

Issues related to machinery aspects of this topic are covered in a companion paper (McPhee & Aird, 2013).

1. Introduction

Controlled traffic farming (CTF) is a system that keeps all machinery traffic associated with cropping operations in the same wheel tracks year after year. Controlled traffic is instrumental to achieving many benefits such as reduced energy use (Lamers, Perdok, Lumkes, & Klooster, 1986; McPhee, Braunack, Garside, Reid, & Hilton, 1995a; Tullberg, 2000; Voorhees, 1979), improved soil health (Stirling, 2008) and crop yield (Chen et al., 2008; Dumas, Trouse, Smith, Kummer, & Gill, 1975), better timeliness of field operations (McPhee, Braunack, Garside, Reid, & Hilton, 1995b; Spoor,

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Nomenclature

GNSS	global navigation satellite systems
RTK	real time kinematic
CTF	controlled traffic farming
SCTF	seasonal controlled traffic farming

Miller, & Breay, 1988) and improved economics (Bowman, 2008; Chamen & Audsley, 1993; Kingwell & Fuchsbichler, 2011; Loeskow, Cameron, & Callow, 2006).

Many factors influence the successful adoption of CTF. Investigations were undertaken, using the Tasmanian vegetable industry as a case study, into two of the essential elements of an efficient and effective CTF system, namely:

- the feasibility of equipment changes (particularly harvesters) required to allow successful implementation of CTF
- the design of pilot CTF farm layouts to assess the feasibility of various layouts in steeply undulating topography, and particularly to determine if the current practice of operating up and down slope was consistent with good CTF layout principles

This paper reports on the second of these issues, the first being reported in McPhee & Aird (2013).

The topography of many vegetable farms in north-west Tasmania is complex. This raises issues in relation to farm layout, operational logistics, drainage, irrigation and erosion under any farming system, but particularly one that requires self-draining, compacted wheel tracks. Erosion of compacted wheel tracks is perceived to be a significant issue for CTF in the Tasmanian vegetable industry.

Research and grower experience in broadacre grain growing areas indicate that runoff can increase under down slope controlled traffic systems relative to across the slope orientations (Titmarsh et al., 2003). Whether or not this increases erosive soil loss is very dependent on levels of ground cover, infiltration in the non-wheeled area, slope and length of run (Titmarsh et al., 2003). Yule (1995) identified three key principles to controlling erosion, namely: optimisation of infiltration, layout to control the direction and volume of runoff, and safe disposal of runoff. It is well established that CTF improves infiltration, and hence reduces the amount of runoff from the untrafficked cropping zone (Bai et al., 2009; Braunack & McGarry, 2006; Lamers et al., 1986; Li, Tullberg, & Freebairn, 2007; Tullberg, Yule, & McGarry, 2007). Down slope CTF orientation spreads runoff more evenly across the field, thereby avoiding the risk of runoff concentration, and subsequent breakout and excessive soil loss through rill erosion, as often happens in across slope orientations (Yule, Cannon, & Chapman, 2000).

The percentage area devoted to wheel tracks in broadacre cereal CTF systems is considerably less than would be the case in vegetables – 10% compared to >30% for many vegetable systems. In addition, crop residue retention through the use of zero-tillage practices is a feature of most grain farming areas, but not a practice of any note in vegetable production. Nevertheless, it is likely that improved infiltration under CTF would reduce run-off, and hence erosion, even in a vegetable CTF system (Li, Tullberg, & Freebairn, 2001; Li et al., 2007).

A number of issues impact farm layout in vegetable production, such as:

- field shape and size
- complexity of topography – planar, convex, concave, undulations, slope
- length of run for harvest haul out, irrigation, pesticide application, and operational efficiency
- the need for a range of specialised machinery for crop production
- irrigation technology and infrastructure
- physical barriers – trees, fences, roads, drains, buildings
- isolated field features – e.g. rocky outcrops
- inter-property water management
- accurate machine tracking in areas of side slope
- erosion and surface drainage
- poor levels of ground cover in typical vegetable cropping
- access for daily operations
- crop type

An effective controlled traffic farming system requires the farm to be planned for efficient field operations, which includes direction of travel, machinery, drainage, erosion and irrigation. Where drainage and erosion issues can be influenced by topographic features beyond the boundaries of the farm, it is best to design adjacent farm layouts to capitalise on drainage paths and water capture opportunities, although is often not possible.

The topography of Tasmanian vegetable farms ranges from flat and poorly drained in the midlands areas of the State, to undulating with complex shape profiles and numerous surface drainage pathways, in the north-west and north-east regions.

Tasmanian vegetable farms have a number of features that are significantly different from the expansive and relatively flat properties of the dry land cereal industry in the mainland Australian states. Vegetable farms tend to be small, with less than 100 ha common. Fields also tend to be small. Headland areas used for turning at the end of a row can account for up to 5% of the field area. Farms are often impacted by, or impact upon, other properties that are up or downslope in the landscape e.g. through management of runoff.

Current irrigation technologies have an influence on field size. Travelling and linear move irrigators tend to have a maximum hose length of around 300–400 m, which dictates the maximum length of run in any field. The uptake of centre pivot irrigators in the vegetable industry in recent years has seen the removal of many fences, but field layouts have not been designed with CTF in mind.

For all of these reasons, the design of CTF layouts on Tasmanian vegetable farms presents some challenges that are not present in broadacre grain growing regions, such as those in Australia or Canada, where CTF for grain production is becoming more widely adopted. Similar constraints are likely to occur in other vegetable production regions, particularly in relation to irrigation infrastructure and length of run for optimising materials handling operations, such as harvest and spraying (Bochtis, Sørensen, Green, Moshou, & Olesen, 2010; Bochtis, Sørensen, Jørgensen, & Green, 2009).

While the focus of this work was the undulating regions of the Tasmanian vegetable industry, the findings are applicable to any CTF enterprise operating in a complex topography.

2. Materials and methods

Layouts were designed for a number of farms representative of north-west Tasmania to investigate some of the issues of CTF layout for vegetable farms. The farms represented a diversity of situations, from relatively flat and simple in terms of existing fixed infrastructure, to steeply undulating with small fields. Survey data of fixed infrastructure (roads, fences, buildings, windbreaks etc.) and topography was obtained from prior ground-based mapping data which had been generated as a result of other unrelated farm planning projects. Similar data could be obtained from tractor-mounted RTK GNSS (Real Time Kinematic Global Navigation Satellite System) equipment, although at the time this work was done, such systems were not in widespread use in the Tasmanian industry. The most detailed publicly available maps are 1:25,000 scale, which are not as suited to this type of planning work as the data used.

A number of principles, which have been developed through experiences in the Australian grain industry, were applied to the process of developing farm layouts in this work. These include:

- a whole of farm approach
- the use of accurate topographic mapping data of RTK level accuracy
- drainage design such that each furrow or row carries its own run off, which will generally require field operations to work up and down slope wherever possible
- layout for field operational efficiency, as influenced by length of run and field shape
- provision of road access for operational servicing and removal of harvested product
- placement of access tracks on ridgelines to aid drainage and ensure access tracks are least affected by wet conditions

Working through these principles provides a sequenced guide to the issues which must be addressed when designing a farm layout for controlled traffic. Another issue, not covered in this work, is consideration of the cost:benefit of the change. This is a topic worthy of a study in its own right, which goes far beyond the issues of layout, and includes consideration of the costs of machinery modification and the benefits likely to be gained from the adoption of controlled traffic in relation to yield, timeliness, reduced input costs etc.

The layout design for controlled traffic was approached in two different ways for each farm. Firstly, a layout was designed that accommodated the existing field and infrastructure constraints. This provided a comparison to current (i.e. non-controlled traffic) layouts and directions of field operations. A second layout was designed which ignored the constraints of existing infrastructure or features such as fences, poorly sited roads, outlier trees and irrigation systems. This was done to determine the level of improvement that could be obtained by removing or re-locating obstacles that interfered with an efficient layout.

3. Results

The following discussion and illustrations relate to three of the farms used as case studies in this work. Three farms are included as they represent quite different examples, including differences in size, irrigation infrastructure and degree of change required to implement an effective controlled traffic layout. Some of the key characteristics of the farms are:

- Farm 1 – relatively small farm (40 ha total, 30 ha used for cropping), reliant on travelling irrigators, and requiring minimal change in layout for controlled traffic implementation. Slopes on the farm range from <5% to >35%, with the majority of the land in the main cropping areas being 5%–20%. Length of run in the original farm layout ranged from 150 m to 335 m.
- Farm 2 – a medium sized farm (120 ha total, 95 ha used for cropping), with most of the area serviced by a linear move irrigator, and able to achieve an acceptable layout for controlled traffic with minimal change, but requiring some significant change to achieve the best layout. Slopes on the farm range from <5% to >35% with the majority of the land in the main cropping areas being <15%. Length of run in the original farm layout ranged from 145 m to 485 m.
- Farm 3 – a large farm (260 ha, 250 ha used for cropping), with centre pivot irrigators, reliant on travelling irrigators for some fields, and able to achieve an acceptable layout for controlled traffic with minimal change, but requiring significant change to achieve the best layout. Slopes on the farm mainly range from <5% to 25%, with small areas up to 35%. The majority of the cropping area is <15%. Length of run in the original farm layout ranged from 240 to 590 m.

Each of the farms is illustrated using an aerial photograph showing contours, fences, roadways and current directions of run for field operations. In each case, this is followed by additional illustrations showing alternative layouts to meet the requirements of an effective CTF layout.

The equipment used on these farms is representative of that commonly used on Tasmanian vegetable farms, as outlined in McPhee & Aird (2013). Tractor wheel gauges would normally be 1.625–1.73 m, as determined by the requirement for growing potatoes, and crops grown include the range of vegetable and non-vegetable crops common to the region (potatoes, carrots, onions, beans, peas, broccoli, cereals, pyrethrum and poppies), with a consequent variety of machinery used for land preparation and harvest.

3.1. Farm 1

Current directions of operations for one of the farms are shown in Fig. 1. Within the constraints of existing fences, roads and irrigation systems, the practicalities of field logistics indicate that directions of run do not change for a CTF layout. However, there is a risk of drainage failure in the area indicated by ‘A’. This area has a very low slope which transitions to a ‘side slope’, leading to a natural drainage path across the direction of field operations travel. The low slope of the area indicated at ‘Á’ makes it difficult to construct a practical drainage option to intercept flow.

A suggested layout for the same farm, assuming no infrastructure constraints, is shown in Fig. 2. While some fields retain the same work direction, changes are suggested for the layout of access roads and the directions of run for other fields to make the best use of slopes for surface drainage. In cases such as this, surface drainage would be provided by the construction of broad-based grassed drains to allow carriage of overland flow at non-erosive speeds. Access roads would be re-routed to ridge lines to minimise drainage impacts, and provide the driest part of the landscape for haul out operations. Re-orientation of some fields to a diagonal direction of run, as in the proposed layout, requires greater headland areas and results in short run-out rows in the corners. On a relatively small farm engaged in the production of high value crops, increasing the area of headlands and turning could be a significant constraint.

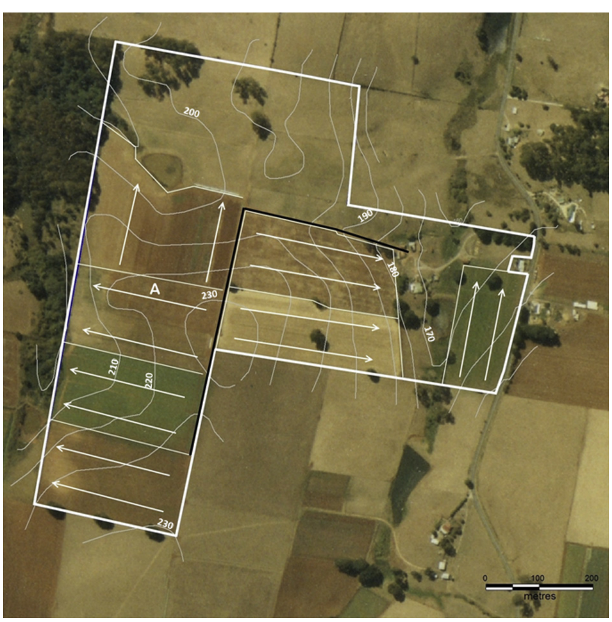

Fig. 1 – Existing layout out of first farm. Layout for CTF within existing constraints does not change the layout, but there is a risk of surface drainage failure in the area marked ‘A’. Farm roads and tracks are marked in black. Fences are marked in white, thin lines for field fences and a thick line for the property boundary fence. The direction of run for field operations is marked in white lines with arrows. Lines with a single arrow head indicate the direction of run coincides with the dominant direction of fall for the slope of the field.

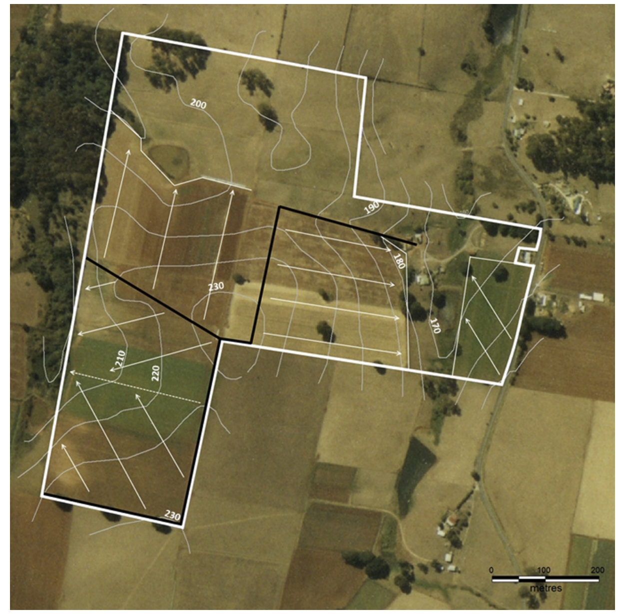

Fig. 2 – Proposed layout of first farm for CTF without constraints, showing re-direction of operational runs in some areas, and relocation of roads to assist drainage objectives. Dotted white lines with an arrow head indicate suggested drainage lines for improved surface drainage.

3.2. Farm 2

An aerial photo map of the second farm shows the current directions of operations in each field (Fig. 3). A linear move irrigator services all fields either side of the central road. Within existing constraints, and the practicalities of field logistics, the direction of run layout does not change for a CTF layout. However, several drains are required to improve surface drainage and reduce the risk of erosive breakout across slopes during heavy rainfall (Fig. 4). A possible layout, assuming no existing infrastructure constraints, is shown in Fig. 5. While some fields retain the same work direction, changes are suggested for the direction of run for other fields in order to make the best use of slopes for surface drainage. This also reduces the number of constructed drains required, because the re-oriented directions of run provide positive

Fig. 3 – Existing layout out of second farm showing directions of run for field operations.

Fig. 4 – Layout out of second farm for CTF operation within existing constraints, showing location of surface drains to reduce risk of erosion and drainage failure.

drainage for most areas of the farm. Exceptions can be managed by the installation of surface drains as indicated (Fig. 5). Access roads have been re-routed to ridge lines to minimise drainage impacts.

3.3. *Farm 3*

Current travel directions for operations on the third farm are shown in Fig. 6. These are largely dictated by slope direction, although there are a number of fields where the direction of run is essentially across the slope. This farm features a number of centre pivot irrigators, which can present drainage issues under controlled traffic layouts. Preferential flow of water in the wheel tracks, particularly where the tracks run along the contour, can cause an accumulation of water, and subsequent break-out, leading to erosion at the break-out point. The preferred direction of travel for a CTF layout is constrained by existing fence, road and irrigation infrastructure (Fig. 7). This results in a number of fields with short or diagonal runs in a re-configured layout. While this makes best use of the slope for drainage, it is likely to be less efficient for field operations. Surface drains are required to manage run-off from some areas.

A suggested layout for the same farm, assuming no constraints of existing infrastructure, is shown in Fig. 8. A number of areas maintain the current direction of travel, although other parts of the farm would require re-orientation for optimum implementation of CTF. This would have significant implications for irrigation infrastructure. Some roads would need to be re-aligned to make better use of higher parts of the landscape. This is generally preferred as the roads then have minimal effect on surface drainage. Upslope road verges also provide ideal locations for interception drains to limit run-on of overland flow to the field.

Although it would be possible to operate this farm in the layout shown in Fig. 7, it would function more effectively from a drainage and vehicle movement perspective if it were laid out as shown in Fig. 8.

Fig. 5 – Layout out of second farm for CTF operation without constraints, showing re-orientation of operational directions for some fields.

Fig. 6 – Existing layout out of third farm showing directions of field operations.

4. Discussion

The success and efficiency of CTF operations can be greatly influenced by farm layout, which impacts field efficiency, product removal at harvest, irrigation, surface drainage and

Fig. 7 – Layout out of third farm for CTF operation within existing constraints, showing location of added surface drains to reduce risk of erosion and drainage failure.

Fig. 8 – Layout out of third farm for CTF operation without constraints, showing re-orientation of operational directions for some fields and location of surface drains required for improved overland flow management.

erosion management. These issues need to be considered irrespective of the industry or the environment in which CTF is being established, although their relative importance will be influenced by the crop, topography and rainfall. The following discussion addresses these issues in general terms, using the example farms to demonstrate particular points. The discussion focuses on the vegetable industry, although the basic principles are relevant to any cropping industry.

It is generally accepted that the most efficient layout is one that provides long operational runs, thereby minimising the time and area devoted to headland turning. Modelling by Bochtis et al. (2009) shows the constraints of fixed traffic directions under controlled traffic can significantly impact field efficiency, particularly for materials handling operations. Further, while longer runs may improve field efficiency, they might not always be the most economical choice (Bochtis, Sørensen, Busato, et al., 2010). However, it is noted that the major portion of the increased cost associated with long runs in this modelling was due to "lost material" – i.e. material such as pesticides and fertiliser which was wasted due to over-lap. The increasing use of GNSS guidance and section control on many materials application implements should make this loss negligible, and therefore favour longer runs as both more efficient and more economical. The preference for longer operational runs is illustrated in the original layout of Farm 1 (Fig. 1) and the unconstrained layout of Farm 3 (Fig. 8).

One of the key operational considerations in layout design in the vegetable industry is the harvest efficiency as dictated by the frequency of unloading of harvested product. The crops with the greatest materials handling requirements in the Tasmanian industry are potatoes, onions and carrots. The dominant harvester style used in the Tasmanian industry is a single row bunker harvester, although some twin bed harvesters are used for onions. When used for potato harvest, single row harvesters have a working width of 813–864 mm, depending on row spacing (McPhee & Aird, 2013). When used for onions, a single bed (1.625 m or 1.73 m) is lifted and windrowed to a width suitable for the single row harvester intake, which is modified for onion recovery. Twin bed harvesters recover two such adjacent windrows per pass.

Considerations of the yield range and the bunker capacities of root crop harvesters, or chaser bins where appropriate, indicate a limiting row length of approximately 400 m. This is for the situation of a high yield onion crop (90 t ha^{-1}) harvested by a twin bed harvester using a 12 t chaser bin. For a median yielding crop and the same harvester configuration, the row length required to fill the chaser bin would be 550 m, while for a single bed harvester, the distance would be double. In the original layout configurations discussed in this paper, the maximum row length is 335 m, 485 m and 590 m for farms 1, 2 and 3, respectively. In the revised layouts with no infrastructure constraints, the maximum row lengths for farms 1, 2 and 3 are 275 m, 570 m and 760 m, respectively. Therefore, some of the longer row lengths that arise due to reconfigured layout may enforce additional consideration of harvest logistics, depending on the crops grown and the harvest technology used.

Field operations generally take place up and down slope in the Tasmanian vegetable industry. This practice has arisen in order to maximise operator safety and operational efficiency, such as maintaining parallel crop rows when planting, and accurate tracking of trailed equipment, such as root crop harvesters. This is a feature of many production areas with undulating topography. Up and down slope operation tends to favour more effective equipment operation and management of surface drainage under controlled traffic operations, although there is still potential for erosion in the wheel tracks (Titmarsh et al., 2003). The preference for up and down slope operation for surface drainage purposes is a feature of the layouts suggested for the illustrated farms.

The objective of layout design for drainage is to ensure positive drainage is maintained in all wheel tracks, and this has been the emphasis in the re-designed layouts. This can be difficult in areas with complex landscapes, as it is inevitable there will be parts of the field in which the direction of travel runs along the contour, or at a shallow angle, rather than across it. Because of the complexities of the landscape in Tasmania, many farms have areas that are at risk of drainage failure because of this issue. The most difficult situations arise when there are 'reverse grades' which provide the opportunity for accumulation of run-off water.

There is insufficient experience in the Tasmanian environment to judge whether wheel track erosion under CTF will be an important issue, although it is unlikely to be any more of an issue than already exists in current cropping systems, which often rely on seasonally established beds or ridges, depending on crop requirements. Observations of heavy rainfall events on controlled traffic demonstration and research sites suggest that run-off will be significantly reduced under CTF operation due to improved infiltration in the crop beds (unpublished data). It is expected that currently used techniques to minimise soil erosion, such as rip mulching (Cotching, 2009, pp. 47–51), would continue to be part of erosion management under a controlled traffic system.

One opportunity for improving efficiency and operational logistics in CTF is the removal of fences to create bigger fields. Turning areas and headlands are important aspects of CTF layout, and the influence of run-out rows can be significant, particularly in irregularly shaped fields. Current farming systems use the headlands for crop production, and growers regularly invest more tillage effort in these areas to counter the effects of intensive traffic at harvest. In an ideal scenario, headlands under controlled traffic would be permanently grassed, and managed for traffic movement and effective surface drainage. However, in a typical regular shaped field of 250 m length, headland area would normally represent 4–8% of the field area. This is a significant area in a region with high land prices and producing crops that require significant investment and provide high returns per hectare. Longer fields reduce the area of land devoted to headlands and turning areas, although such a change is only possible if irrigation systems are not limited by fixed supply hose lengths, and consideration is given to harvest logistics, as outlined earlier.

The other aspect that may require change is re-alignment of access roads to make the best use of high points in the landscape, which helps implementation of more efficient surface drainage, as well as providing the driest possible access to the field.

Most CTF layouts will need to be designed within existing constraints, particularly irrigation infrastructure, which has the potential to complicate CTF layout. The Tasmanian vegetable industry makes extensive use of centre pivot irrigators, which inevitably leave wheel tracks that cut across the direction of travel for CTF operations. Track maintenance operations may be needed to ensure adequate drainage from irrigator wheel tracks. Lateral move irrigators may be a better choice in some cases.

5. Conclusion

Key issues to address in vegetable farm layout design for the successful adoption of CTF are the integration of irrigation, fence and road infrastructure with materials handling, drainage and erosion management requirements.

A desktop farm layout design exercise indicated the working direction of many fields in the Tasmanian vegetable industry is already consistent with good CTF layout principles, such as operating up and down slope to provide positive track drainage. In some cases, relatively simple changes to farm layout would improve the farm design for CTF. Some areas would be difficult to achieve effective surface drainage, and installation of strategic surface drains may be required in these situations. While these issues are particularly apparent in complex landscapes, the general principles must be considered for layout design in any industry or topography.

One issue of concern is the risk of erosion in the wheel tracks of an up and down slope CTF system. The reality is that existing farming systems already face this issue, and with improved infiltration in the crop zones, it is envisaged the situation will improve with CTF. This issue requires further investigation.

The alternative layouts discussed highlight the importance of investigating farm layout before making significant changes or investments in infrastructure such as irrigation, particularly in the context of whole-of-farm implementation of CTF.

Good quality information is critical to the development of the best possible layout. This includes information about the:

- topography, preferably from RTK GNSS
- location of infrastructure
- cropping system, and machinery used.

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3.2 Discussion – Machinery matters

The fundamental basis of controlled traffic is dimensional integration of machinery, such that track gauge and working width is either common or meets some modular pattern across all machines (Baker et al., 2007). The challenge of dimensional integration of machinery occurs in several cropping industries, although the vegetable industry is arguably the most complex, due to the diversity of crops grown and the consequent diversity of machinery used in their production. The differences in commonly accepted spatial arrangements between crops, along with differences in plant architecture and the nature of the harvested part, all contribute to the diversity of mechanisation in the industry, particularly in the case of harvesters (McPhee et al., 2018). This diversity presents a wide range of track and working widths that need to be accommodated or managed if viewing the production system from a controlled traffic perspective. This issue is accentuated where the production system includes combinable crops (e.g. cereals) in rotation with vegetables. Common Tasmanian crop rotations also include poppies and pyrethrum which introduce additional machinery considerations (McPhee & Aird, 2015). Even without this added complexity, vegetable production systems that rely on specialised mechanical harvesters (as distinct from hand harvest) will generally be faced with machinery designs that are incompatible with the dimensional integration requirements of controlled traffic.

Most changes to machinery to enable adoption of controlled traffic in other industries have been grower led, hence there are few reports in the peer-reviewed literature. Those that have been published date back to the developmental days of permanent bed farming in the 1970's and 80's (Adem & Tisdall, 1984; McPhee et al., 1995a; Morrison, 1985), and often relate to specific circumstances of soil or crop type. The analysis reported in Chapter 3 (McPhee & Aird, 2013), undertaken to identify potential barriers to adoption of controlled traffic in vegetable production, outlines some of the specific issues faced by the Tasmanian industry in achieving dimensional integration, a point that is also relevant in other countries (Johansen et al., 2015). To date, this paper is the only published industry-focused assessment of the challenges posed to the adoption of controlled traffic as a consequence of crop and machinery diversity.

Controlled traffic is not about a specific track gauge. The aim is to minimise the area of the field impacted by traffic and isolate it into permanent traffic lanes. Achieving that in the simplest fashion possible is a key criterion for track gauge selection, while at the same time recognising the benefits of making the track gauge as wide as possible to maximise the uncompacted cropping zone.

General advice for growers wishing to adopt CTF is to focus on the harvester first, as it is the most difficult machine to modify (Tullberg, 2006) and has the potential to do the most damage to soil on account of its mass. As a consequence, the grain industry uses a 3 m (or 120 inch if based on non-metric designs) track gauge, which is close to a standard track gauge for many grain harvesters. Several commercial providers now have modification solutions for various types of machinery based on a 3 m track gauge. Due to crop diversity in the rotation, the vegetable industry has several 'most difficult to modify' machines, some of which offer no potential for modification to suit controlled traffic systems (e.g. tri-cycle carrot harvesters). A number of track gauge options were proposed in Chapter 3 (McPhee & Aird, 2013). The options chosen – a vegetable/other crops hybrid of 1.7/3.4 m, 3 m for all crops, and a hybrid of 2 or 2.5 m for vegetables and 3 m for combinable crops – were all chosen with a view to minimising modifications to existing machinery. Even so, none are ideal solutions, and all would require significant change to at least some current industry machinery configurations. Of the options proposed, the hybrid 2 (or 2.5) m and 3 m system is a reasonable compromise, even though it would still require extensive machinery modification across the industry (McPhee & Aird, 2013).

3.2.1 Impact of tyre width

The harvester is often the largest and heaviest machine used in the cropping cycle, and across a range of industries, many harvesters exceed 20 Mg loaded mass, with some vegetable harvesters exceeding 50 Mg when loaded. Wide section tyres or tracks are used to carry these heavy loads and to improve flotation and trafficability under wet conditions. This presents challenges for controlled traffic. Although the correct track gauge may be achieved to satisfy track position requirements, tyre width is often larger than the furrow or traffic lane in row crop systems. This can result in the need for remedial tillage along the edges of cropping beds (McPhee et al., 2015). With track gauges used in vegetable production commonly being in the range of 1.5-2.0 m, even if all machinery could be matched for track gauge, it would be very difficult to reduce tracked area below 25% for large machinery and in some situations, the tracked area would be closer to 40%. The use of narrow rubber belts may be an option in some circumstances, but even so, 20% tracked area is likely to be the lower limit.

While controlled traffic may be a constraint on the use of wide tyres, it is also a potential solution for avoiding (or at least minimising) their use. Wide section tyres are often fitted to large tractors used for high draft tillage operations in conventional farming systems. A key benefit of controlled traffic is the reduction in tillage required, both in terms of the number of operations (McPhee et al., 2015) and the draft requirements (Dickson & Ritchie, 1996; McPhee et al., 1995b; Tullberg, 2000). This can lead to the use of smaller tractors fitted with narrower tyres which can avoid soil impacts outside the permanent track (Adem & Tisdall, 1984; McPhee et al., 1995a).

3.2.2 Transport logistics

Road transportation is another factor to consider when selecting track gauge, as noted in Chapter 3 (McPhee & Aird, 2013). By rural standards, vegetable production areas tend to be densely populated, and movement of agricultural equipment on roads is common. Tasmanian regulations permit the passage of vehicles with a total width of less than or equal to 3.5 m, which would accommodate a 3 m track gauge with 500 mm section width tyres. Safety and logistics considerations (e.g. on narrow rural roads) often dictate that a narrower track gauge is preferable. A potential solution to the issue of requiring a wide track gauge in the field and a narrow one on the road has appeared in recent years in the form of the Multi Tool Trac, a prototype diesel-electric tractor from the Netherlands with on-the-go adjustable track gauge from 2.25-3.25 m (MultiToolTrac, 2019).

3.2.3 Tillage

The adoption of controlled traffic can have a significant influence on the tillage machinery requirements of a farming system. Tractor power can be reduced, and fewer, and sometimes different, tillage implements can be used. Even if the same tillage implements are used, they will generally be used less often. Research in the Tasmanian vegetable industry showed a lot of similarity in the type of tillage operations used under controlled traffic and conventional management, the main difference being the number of tillage operations (McPhee et al., 2015).

A common feature of final seedbed preparation in the vegetable industry is the use of packer rollers or smudge boards to leave a smooth, fine tilth suited to current seeding equipment, which has very limited capacity to cope with crop residue. Such seedbed conditions are susceptible to erosion and reduced infiltration during irrigation or rainfall. An alternative approach, using a wire roller attached to the rear of other implements (Figure 3-1) leaves a slightly roughened seedbed that is still suitable for conventional seeding machinery (J. McPhee, unpub. data). This type of roller has been successfully used in previous permanent bed, controlled traffic research (Adem & Tisdall, 1984; McPhee et al., 1995a) and was also used effectively (although not reported) in the field research covered in Chapter 4 (McPhee et al., 2015).

Figure 3-1. Wire roller used after ripping to provide final seedbed condition.

Part of the value of the wire roller is that is provides a light tilling operation on the surface of the bed, helping to level the soil surface whilst leaving a tilth that is suitable for sowing small seeded crops and also retaining some surface roughness to aid infiltration. Figure 3-2 shows the difference in surface condition of a seedbed resulting from a conventional rotary harrow bed-former with smudge boards, compared to a wire roller.

Figure 3-2. Bed surface condition formed by a smudge board bed former (left) compared to the wire roller (right).

3.2.4 Tractor and implement stability

A key operational issue observed during field trials of controlled traffic in the vegetable industry was the difficulty of tractors maintaining stability on compacted traffic lanes, particularly in undulating topography with side slope (J. McPhee, unpub. data). In conventional production systems, the entire cropping zone is established over a base of sub-soil compaction, and the surface soil is fully disturbed to the depth of tillage. This provides uniform soil conditions in relation to tyre-soil interactions, with support at depth from a persistent, compacted layer of soil. The controlled traffic environment is quite different, with the field made up of alternating zones of highly compacted tracks, separated by friable crop beds with little capacity to support heavy loads. Further, in vegetable cropping, it is desirable to keep the wheel tracks narrow (~300 mm wide) to maximise the width of the cropping bed. As noted previously, within the constraints of track gauge and tyre size options in the vegetable industry, it is difficult to reduce wheel track area to less than 25%, compared to ~10% in grain industry CTF systems (McPhee & Aird, 2013). In field trials undertaken in Tasmania, keeping the track narrow was achieved by ripping the interface between the wheel track and the bed to remediate encroachment of wheel track compaction into the cropping bed (McPhee et al., 2015).

Observations of tractor operations at CTF trial sites indicate that the rear tyres of the tractor can easily slip off a narrow, compacted track (Figure 3-3) (J. McPhee, unpub. data). Satellite guidance attempts to steer the tractor back on line, but the key issue is one of trying to keep a large vehicle on a narrow track. This issue was observed in both wet and dry track conditions with draft and non-draft loads on the tractor. A number of factors contribute to this issue:

- desire for wheel tracks and tractor tyres to be as narrow as possible to avoid the impacts of compaction in adjacent crop beds (McPhee et al., 2015)
- loose soil from cultivation operations in adjacent crop beds over-laying the compacted track
- crowning of the track, such that the tyre drives on a convex surface profile
- direction of operations in complex undulating topography, such that machinery is often working on a side slope, even if the direction of travel is predominantly up/down slope, although it is known that the same issue sometimes occurs in flat and low slope landscapes.

Figure 3-3. Sideways slip of tractor on compacted controlled traffic wheel tracks during fertiliser pre-drilling (left) and a non-draft operation, mulching (right).

The tracking issue can also arise when digging potatoes, onions or similar crops. Harvesters used for these crops tend to be long relative to the length of the tractor, with steerable wheels set towards the back of the machine. Lifting and sifting soil, which occurs closer to the tractor, leaves a bed of soft, friable soil. The difference between track and bed condition can make it difficult to keep the harvester on track. There is the potential to use active implement steering to overcome these issues in towed harvesters (Thomasson et al., 2019), although this technology will not address the issue of the tractor falling off the tracks. It is possible that rubber tracks, instead of tyres, on tractors may help prevent, or at least reduce, this problem. Narrow (300-450 mm wide) rubber track conversion kits have become more readily available in recent years. Further, if the configuration of the track was such that it deformed over the top of the convex compacted soil, it may be quite effective in addressing this problem. Mitigating against this solution is the potential cost. Observation suggest that while narrow rubber tracks are marginally cheaper than wider tracks, their life span is significantly lower, particularly in situations incurring significant road travel, as is the case for contractors (D. Darby, Highlees Harvesting, pers. com.).

3.2.5 Track maintenance

Compacted wheel tracks form an important part of controlled traffic systems. In conventional systems, wheel track compaction is removed with intensive post-harvest tillage. In controlled traffic systems, compacted wheel tracks are an advantage, giving benefits of timeliness, reduced rolling resistance and savings in tillage energy not invested in their removal (Monroe et al., 1989; Taylor, 1983; Tullberg, 2000). Given their centrality to the success of controlled traffic, maintenance of wheel tracks has assumed a degree of importance, and various implements have been designed for the task.

Rotary furrow cleaners have been used experimentally to remove accumulated silt and stubble out of the furrow and place it back onto the bed, leading to improvements in surface drainage and subsequent trafficability (Adem & Tisdall, 1984; McPhee et al., 1995a). Manufacturers supporting the grain industry have developed different styles of wheel track renovator to address the issue of track maintenance (Isbister et al., 2013).

Because of the previously mentioned issue of tractor and implement stability on narrow, compacted wheel tracks, limited controlled traffic experience in the Tasmanian vegetable industry has led to a track maintenance approach that runs counter to the objective of maintaining compacted wheel tracks. The most successful approach to addressing this issue to date has been to cultivate the wheel track to a depth of approximately 100 mm. This removes the convex profile of the compact track and allows tyres to sink into loose soil on the subsequent pass (M. Kable, Harvest Moon, pers. comm.). While the surface of the track is disturbed, underlying compaction, which helps support the tractor, is retained at depth.

3.2.6 Examples of vegetable CTF systems

Despite the many machinery barriers to controlled traffic adoption in vegetable production, degrees of success have been achieved in a variety of circumstances. Early controlled traffic work in vegetables in the Netherlands was based around potato production, with the choice of track gauge (3.3 m) being a multiple of the potato ridge spacing (750 mm) plus an allowance for tyre width, such that the tractor straddled four rows (Lamers et al., 1986). Others have managed with very simple changes, such as the extension of the axle of a potato harvester by the width of one row to achieve matching track locations between tractor and harvester (Powrie & Bloomer, 2010). Such simple changes are very machine specific and not applicable as a generic solution in the vegetable industry.

There is some attraction in the adoption of a 3 m track width for vegetables, not least being that it would match with grain harvesters. One large-scale Australian vegetable grower has adopted a 3 m track gauge and working width using custom-designed bean and sweet corn harvesters to match with grain harvesters (Johanson, 2020). This system works because of a relatively simple vegetable cropping rotation that does not include any root or tuber crops. While clearly a successful system for the operator, it does not provide a generic solution for controlled traffic adoption in the vegetable industry.

Hand-harvested and specific bed-grown crops present another alternative for adoption of controlled traffic in vegetable production. Hand-harvested crops generally require the use of a tractor mounted harvesting aid, so the incompatibility of specialist harvester dimensions is not an issue. Alternatively, specialist machinery for specific crops can be designed to straddle a bed (e.g. salad leaf harvest, Figure 3-4) One Tasmanian operator has adopted a 2 m track gauge for all machinery that can be bought with that track gauge, or modified to suit (Figure 3-4), but a fully integrated controlled traffic system is used only on a specific part of the growing operation. Flat land growing hand-harvested and other specific vegetables has been established as permanent beds, with each implement pass covering 3 beds, each 2 m wide. This change has reduced tractor size by approximately 50% and tractor hours by approximately 30% (Kable, 2019). In addition, the inventory of tillage machinery has simplified (now ground-driven or passive implements instead of powered) and reduced (fewer implements).

Figure 3-4. Tractor-based controlled traffic, permanent bed system used for growing a specific range of vegetables suited to hand or specialised equipment harvest, showing 3 x 2 m bed tillage (left) and spinach leaf harvest (right).

In the absence of readily adoptable solutions to the track gauge dilemma of mechanised harvest, some growers have adopted Seasonal Controlled Traffic Farming (SCTF), in which all field operations except harvest are undertaken on the same wheel tracks. The system is not widespread, although two Tasmanian growers have adopted the practice (M. Nichols, Redbank Farming, and J. Addison, Charlton Farms, pers. com.). While benefits have been reported from the adoption of SCTF (Vermeulen & Mosquera, 2009), the rate of change in soil improvement is inevitably slowed due to seasonal harvest traffic and the need for remedial tillage.

Given the lack of readily available controlled traffic compatible machinery and standardisation of crop spatial configurations, vegetable growers tend to have two choices when it comes to achieving some level of traffic control:

- For systems that are not dependent on dimensionally incompatible harvest machinery (i.e. predominantly hand-harvested crops), permanent beds are an obvious option (Rogers et al., 2001).

- Where harvest machinery design prevents the adoption of a fully integrated controlled traffic system, seasonal controlled traffic is an option, such that all operations except harvest are conducted on the same track gauge and from the same tracks, with satellite guidance allowing return to permanent wheel track locations after harvest (Vermeulen et al., 2010).

In the longer term, the most promising avenue for addressing this issue, while also keeping the percentage area devoted to wheel tracks to ~10%, is the use of wide-span gantries, as discussed by (Chamen et al., 1994; Hood et al., 1987; Tillett & Holt, 1987) and in Chapter 6 (Pedersen et al., 2016) with specific reference to the vegetable industry. Such an approach would use the wide span as the base unit for multiple operations, and hence there would be only one track gauge. All implements and harvesting technology would be mounted on the wide span frame.

3.2.7 Change challenges

Not all the machinery related barriers to change are mechanical. Machinery ownership adds to the complexity of the situation in the vegetable industry, as many operations (harvest in particular) are undertaken by contractors. In some cases, the harvesters are owned by the company that contracts to buy the vegetables for either processing and freezing or fresh market packing. As outlined in Chapter 3 (McPhee & Aird, 2013), while some corporate owners of such machinery may have the capacity to fund modifications to enable controlled traffic, there is little incentive unless all operators adopt the same change. Further, although there are broader industry and community benefits to improved soil management, most of the benefits of the adoption of controlled traffic accrue to the grower, with some potential benefits of yield and quality improvement for vegetable processors. Table 3-1 compares three Australian cropping industries that have adopted, to varying degrees, controlled traffic.

Table 3-1. Crop, machinery and industry differences influencing controlled traffic adoption.

Industry	Influence of crop	Machinery suite	Influence of contractors	Changes required for CTF matching
Grain	Similar crop architecture over a wide range of crops	Relatively simple, with same machines used across a wide range of crops	Many self-contained owner-operators, contractors draw from same availability of machinery with some specifically set up for CTF	Basic dimensional changes to track gauge and working width of a limited suite of machines. Most difficult and/or costly are new cutting front and extensions to harvester unloading auger or chaser bin.
Cane	Common crop architecture, although rotation crops introduce differences	Very simple, common harvester design	Whole industry (owners and contractors) draws on same basic designs	Change crop planting configuration to match harvester track gauge.
Vegetables	Many different growth habits and harvested plant parts	Common equipment for tillage, but planting and harvest often dependent on specialist machines used for limited number of crops	Many contractors, particularly for specialist tasks such as planting and harvest. Few grower-owned harvesters.	Many harvesters mechanically difficult to modify, no industry standard for planting configurations between crops.

3.3 Discussion – Layout

Achieving the goal of controlling traffic to the least possible area of permanent traffic lanes requires dimensional integration of machinery and precise guidance. Getting the best performance out of a controlled traffic farming system requires, amongst other things, attention to layout. Layout is important for three key reasons:

- safe management of surface water flow
- efficient logistics
- minimising issues related to accurate tracking of machinery on compacted wheel tracks (as discussed in Section 3.2.4).

The third factor becomes critical in complex topographies in which any given machinery working pass may cross and re-cross contours and inflexion points in the landscape. As outlined in Chapter 3 (McPhee et al., 2013), a well-designed layout for CTF needs to consider a number of factors, most of which relate to topography and constraints imposed by existing infrastructure and farm management practices.

3.3.1 Water flow, trafficability and erosion management

Surface water flow, trafficability and erosion management are inextricably linked issues in the design of controlled traffic layouts, and are important in undulating, planar and flat topographies. Removing excess water from the wheel tracks is critical to maintain timeliness and trafficability advantages while minimising the risk of damage to the wheel tracks. Regardless of how compacted the soil in a wheel track may be, if it is under water, the bearing strength of the soil is reduced, and traffic will risk collapse of the wheel track resulting in rutting. Such damage compounds if not repaired, as the next time rainfall or irrigation occurs, the rut becomes the first place for retention of surface water. This issue may occur in landscapes with very low slope or at inflexion points at the bottom of a slope in undulating topography. Either way, it is important to provide drainage opportunities to enable rapid removal of surface water to allow the wheel track to regain strength before being exposed to traffic. Soil managed under CTF has an immediate advantage, in that infiltration and water holding capacity in the soil between the wheel tracks is increased, resulting in less overland flow accumulating in wheel tracks (McPhee et al., 2015).

The track drainage issue is particularly difficult to resolve in very low slope landscapes subject to irrigation, a common scenario in vegetable production, since some water disposal infrastructure (usually a broad-based drain) needs to be provided at the end of the wheel track or furrow. Even with the best of designs, such drains often remain wet and are subject to traffic damage. The use of dry packs and half-circle sprinklers may provide an option for reducing the amount of irrigation water applied to wheel tracks, but attention also needs to be given to the effects of wind which could cause some areas of crop to be under-irrigated and some water to be applied to the tracks regardless of the measures taken.

The issues are somewhat different in undulating landscapes. There may still be poorly drained portions of wheel tracks, such as at inflexion points at the bottom of a slope in undulating topography, but these will often occur in places where a surface drain can be placed to capitalise on a side slope to aid removal of excess water. In the desk-top mapping work reported in Chapter 3 (McPhee et al., 2013), strategically located surface drains were proposed at some sites to improve functionality of controlled traffic layouts.

The concept of planning layout for traffic to travel up and down slope appears counter-intuitive to reducing soil erosion, but was first used with great success in rain-fed grain production in central Queensland (Cannon, 1998; Yule, 1995). Assessment of the performance of CTF systems designed with downslope layouts showed reductions in soil erosion of up to 90%, with the key factor being that in a downslope layout, each wheel track carries only the surface water from that wheel track. Cross-slope layouts allow water to flow across the slope until it accumulates at a low point, after which it breaks out causing significant rill erosion in the process. In regions where vegetable production occurs on moderate to steep slopes, machinery operations tend to take place up and down slope for safety and operational reasons. Therefore, designing layouts for CTF may not necessarily involve significant change from current practice in terms of working direction, although it must be recognised that most layouts will have some cross-slope component to the direction of travel.

There are significant differences in the <5% slopes reported in work of Yule (1995) and (Cannon, 1998) and those present in the Tasmanian vegetable industry, which can be up to 35%. Compacted tracks on steep slopes are at risk of soil erosion, particularly at the interface between the compacted track and the uncompacted crop zone. Techniques such as rip mulching (Cotching, 2002; Cotching, 2009) could still be used in controlled traffic systems, although there is no experience to indicate how successful it would be in the context of compacted traffic lanes. Another option might be to adapt an approach used by the grain industry primarily for other purposes. Chaff decks are used in some regions of the grain industry to deposit chaff on the permanent wheel tracks. This concentrates weed seed to allow targeted spraying, reduce dust from wheel tracks during spraying and reduce erosion (Isbister et al., 2013). It is this last point that may have value in the vegetable industry, if it was possible to divert crop residue from operations such as carrot or potato harvest into the wheel track. Although vegetable harvest tends to generate much less residue than grain crops, and the residue is often much more prone to decay due to being fresh, this may be an option worth investigation as a possible solution to one of the challenges of managing controlled traffic wheel tracks in undulating topography. Alternative strategies could involve the importation and placement of resilient materials, such as woodchips.

3.3.2 Logistics

Layout influences logistics. A key feature of layouts designed for a 'greenfield' site is to place access roads at high points in the landscape, as shown in Chapter 3 (McPhee et al., 2013). This minimises the risk that access roads will be compromised by rainfall and overland flow. It also ensures the road itself is not a barrier to efficient water flow and management in the cropped part of the landscape.

Logistics, particularly in relation to materials handling, and timeliness are also influenced by the length of working run that is possible within the layout (Bochtis et al., 2010; Bochtis et al., 2009). Machinery operating direction is generally chosen to be parallel to the longest side of the field to maximise working time and minimise headland turning time. This is not always the best choice in terms of water and erosion management, as shown in some of the examples described in Chapter 3 (McPhee et al., 2013). Optimisation of travel direction for water flow and erosion management may result in diagonal layouts that add extra headlands to the field, thereby increasing headland turning time and area. The use of RTK GNSS guidance can minimise the impact of more difficult headland turning by making use of the facility to work alternate bouts.

3.4 Summary

3.4.1 Machinery

Current machinery design is a significant barrier to the adoption of controlled traffic in the vegetable industry. Certain crop combinations (e.g. hand-harvested crops) enable the adoption of permanent beds without the complexity of dimensionally incompatible harvest machinery. Lack of standardisation in crop spatial arrangement, and the diversity of crop type, leads to a diverse range of machines for mechanically harvested crops. None of these harvesters have been manufactured with controlled traffic as a design criterion. Narrow working widths, wide tyres, mis-matched configurations and high operating mass lead to significant soil compaction, both in intensity and extent, followed by excessive tillage as the primary means of remediation. The analysis presented in Chapter 3 (McPhee & Aird, 2013) emphasises the point that the dimensional incompatibility of machinery makes it very difficult for the vegetable industry to reap the benefits of controlled traffic that have been so obviously demonstrated in other industries.

3.4.2 Layout

Layout is an under-recognised component of successful CTF systems. Undertaking field operations in alignment with the slope, as is the case in many undulating landscapes, is in accordance with the preference to design controlled traffic layouts to the same criterion. While many growers in various industries have transitioned to CTF without major changes to farm layout, there are many benefits to designing a layout for optimum performance of the system. These include effective surface drainage while minimising erosion risk, maximising access and timeliness, and optimising in-field logistics. Unfortunately, on most farms, there tends to be only one opportunity to design the optimum layout, which is when the farm is a ‘greenfield’ site. In most circumstance, existing major infrastructure (power supply, dams, irrigation systems etc.) is a major barrier to re-design, as demonstrated in Chapter 3 (McPhee et al., 2013). Optimising layout requires the farming system to be treated holistically, with due consideration given to the possibility of removing or relocating existing infrastructure.

CHAPTER 4. IMPACT OF CONTROLLED TRAFFIC ON SOIL PROPERTIES AND MANAGEMENT IN A VEGETABLE PRODUCTION SYSTEM

4.1 Background

Although the benefits of controlled traffic have been proven over many aspects of crop production systems, it was the ability to isolate the negative impacts of heavy machinery traffic from soil used for growing crops that was the primary driver of early interest in the technique. The use of controlled traffic in studies on the effects of soil compaction on crop growth underscores this focus of early research.

The adoption of controlled traffic in rain-fed grain production has largely been in conjunction with zero-till seeding systems. In part this is because the uptake of controlled traffic often followed the adoption of zero-till, and for those still using tillage, it was soon realised that without the need to remediate traffic impacts, tillage was unnecessary, or at least significantly reduced. Fundamental to the success of controlled traffic is isolation of wheel traffic compaction from soil used for growing crops. Without this separation, the synergistic benefits of the system do not occur.

Even if harvest traffic effects are absent (e.g. in hand-harvested crops), most vegetable production relies on intensive tillage to prepare a fine tilth seedbed suited to currently available seeding and transplanting technologies. Notwithstanding the mechanisation constraints to adoption of controlled traffic outlined in Chapter 3, it is important to understand if it is possible to achieve measurable soil and productivity benefits in a controlled traffic vegetable production system. This line of enquiry was pursued in field research spanning a number of sites, crops and seasons. The first paper in this chapter reports on changes in soil physical properties at two sites, and tillage requirements at three sites, after the implementation of controlled traffic. The second paper reports on the influence of controlled traffic on a specific aspect of soil biology (soil arthropods) at one site over two seasons.

The two papers that comprise Chapter 4 are:

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

Rodgers, D, **McPhee, J**, Aird, P and Corkrey, R, (2018) 'Soil arthropod responses to controlled traffic in vegetable production', *Soil and Tillage Research*, **180**, 154-163

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The effect of controlled traffic on soil physical properties and tillage requirements for vegetable production

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Yield

ABSTRACT

Demands for increased work rates and more timely operations in vegetable production have led to the use of more powerful and heavier machinery over the past 20 years. Increased vehicle weight, frequency of tillage, and capacity to work soil at sub-optimal moisture contents has increased soil compaction, and the tillage effort required for remediation. Despite conclusive evidence from other industries that controlled traffic systems improve soil conditions, reduce inputs, and overall improve productivity, such systems have not been widely adopted in vegetable production. Trials were established on red ferrosols in northern Tasmania to determine the effect of controlled traffic on soil compaction and penetration resistance, and the number of tillage operations required to prepare a seedbed for vegetable production. Potential mechanical, logistical or agronomic barriers to adoption of controlled traffic systems in vegetable production were also identified. Controlled traffic treatments demonstrated improvements in soil physical properties, and 20–60% fewer tillage operations, compared to conventional production systems. However, the measured benefits of controlled traffic were variable over the duration of the research studies due to limitations of current mechanisation. Adoption of controlled traffic in the vegetable production sector is currently limited by track gauge and working width incompatibility across the diverse range of equipment used, and machinery tracking issues associated with undulating topography.

1. Introduction

Controlled traffic farming (CTF) systems require all field machinery to have a common track gauge and working width, or multiple of it, allowing all wheels to be confined to defined traffic lanes (Baker et al., 2007). This permanently separates the crop zone and traffic lanes, which eliminates traffic-induced compaction from the crop growth zone (Chen et al., 2008; Li et al., 2007), allowing the two zones to be managed separately for the optimal performance of both. Traffic lanes are managed primarily to maintain surface drainage and trafficability, and while often left bare, may be planted in some cropping situations (Tullberg, 2010). The non-trafficked crop zone promotes development and maintenance of soil structure, which facilitates greater root development, maintenance of soil organic carbon, and improved infiltration and soil-water storage (Li et al., 2009).

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CTF research has been conducted in many different environments, soils and cropping systems around the world (Bakker and Barker, 1998; Braunack and McGarry, 2006; Chen et al., 2008; Lamers et al., 1986; Tullberg et al., 2007; Vermeulen and Mosquera, 2009). In Australia, CTF research and development has been conducted in sub-tropical, rain-fed and irrigated grain and cotton systems on vertosols, dry land grain on deep sands, and in the sugar cane industry (Blackwell, 2007; Braunack and McGarry, 2006; Li et al., 2007, 2009; McHugh et al., 2009; Tullberg et al., 2007). Few studies have been conducted in irrigated vegetable production systems, on non-vertic soils, or in temperate cropping systems.

Numerous studies have demonstrated that controlled traffic improves soil physical conditions, including reduced bulk density and penetration resistance, and increased infiltration, hydraulic conductivity, and plant available water (Alvarez and Steinbach, 2009; Bai et al., 2009; Chamen and Longstaff, 1995; Li et al., 2007; McHugh et al., 2009; Tullberg, 2010; Unger, 1996). Braunack and McGarry et al. (2006) found significantly lower bulk density and penetration resistance to 30 cm depth in sugar cane controlled traffic trials in north Queensland, Australia. In China, Bai et al.

Nomenclature

GNSS	Global navigation satellite systems
RTK	Real time kinematic
CTF	Controlled traffic farming
SCTF	Seasonal controlled traffic farming
Track gauge	The centre to centre distance between tyres across a machine, perpendicular to the direction of travel

(2009) reported that after 10 years, bulk density in controlled traffic plots was significantly lower (5.2%) at 15–40 cm depth, compared to traditional tillage treatments. Data from a seven year trial in the semi-arid Loess Plateau of northern China also showed significantly lower bulk density at 10–20 cm depth under controlled traffic, compared to conventional tillage and traffic (Qingjie et al., 2009). McHugh et al. (2009) reported that, under zero-till grain production, bulk density at 10 cm depth reduced from 1.38 g/cm^3 to 1.28 g/cm^3 in as little as seven months after cessation of traffic on a vertosol. Reduction in bulk density was attributed to shrink-swell regeneration associated with seasonal changes in soil moisture. They estimated that at the rate of change observed under CTF, the average bulk density in the 0–30 cm layer of permanent beds could reduce from 1.4 g/cm^3 to near natural conditions (1.1–1.2 g/cm^3) after 36 months.

Few studies have reported the effect of CTF on soil water movement and availability. Tullberg et al. (2007) summarised 6 years of data from plots in southern Queensland, Australia, and 5 years of soil moisture data from Shanxi province, China. They measured infiltration of approximately 72% of annual rainfall in tilled wheeled soil, compared to 86% in non-tilled, non-wheeled areas in Australia, and 82–95% for similar treatments in China. Li et al. (2007) also reported rainfall infiltration in controlled traffic zero-tillage treatments was 12% greater than into wheeled, stubble mulched soil. On the Chinese Loess plateau, Bai et al. (2009) found the final infiltration rate of 159 mm/h in a zero-till, controlled traffic treatment was significantly higher than in the traditional tillage treatment (95 mm/h).

In a seven year trial on the semi-arid Loess Plateau of northern China, Qingjie et al. (2009) found that controlled traffic with full residue cover, compared to the conventional treatment of random traffic and full cultivation, had significantly higher soil water content to 150 cm depth at the time of sowing, resulting in 14.2% more water being stored in the soil during fallow periods. Differences in soil moisture between the treatments were attributed to changes in soil structure, tillage practices and residue management. Improved soil structure, as evidenced by lower bulk density and higher infiltration rate, also increased the capacity of the soil to store water. CTF also increased water use efficiency in most years, as increased yield was associated with higher soil water availability (Qingjie et al., 2009). Bai et al. (2009) reported higher volumetric soil moisture (20.5% increase in the 0–30 cm layer during fallow) in a controlled traffic, no-tillage treatment, compared to the traditional random traffic, full tillage treatment. Increased water storage was principally attributed to higher infiltration rates, enabling more rainfall to enter the soil profile.

Adoption of CTF has been shown to influence the timeliness of operations and/or the number of operations required for seedbed preparation (Chamen et al., 1992; Dickson and Ritchie, 1996; McPhee et al., 1995b; Spoor et al., 1988). Conventional vegetable production systems often rely on numerous tillage operations to alleviate harvest-induced soil compaction and prepare a seedbed for the next crop. Controlled traffic systems have been reported to improve timeliness through a combination of: (i) faster work rates due to reduced rolling resistance and improved traction (Taylor, 1983), and reduced tillage draft (McPhee et al., 1995a); (ii) earlier access to the field after rain or irrigation due to improved trafficability, (Dickson and Ritchie, 1996; McPhee et al., 1995b), and, (iii) reduced requirement for tillage (McPhee et al., 1995b; Tullberg et al., 2007).

In Tasmania, as elsewhere, opportunities exist for adoption of reduced or zero-tillage in vegetable production in conjunction with controlled traffic (Vedie et al., 2008), although current practices typically involve numerous passes of heavy machinery and intensive tillage to remediate the effects of harvest traffic. Traffic loads for crops such as potatoes, carrots and onions often exceed 300 t km ha^{-1}, while the seasonal tracked area is 3–5 ha ha^{-1}, with harvest operations contributing over half of the tracked area, resulting in close to 100% ground coverage over the crop cycle (McPhee, unpub. data). Similar loads and coverage intensity have been reported for vegetable production systems elsewhere in the world (Domzal et al., 1991; Kuipers and Zande, 1994).

In the red ferrosols, which are favored for vegetable production in Tasmania, Cotching et al. (2004) reported that current tillage and traffic practices led to reduced soil carbon and detrimental impacts on soil physical properties. Fields used for continuous cropping showed declines in soil organic carbon in the top 150 mm of 30%, and declines of microbial biomass carbon of 60%. Changes in soil physical properties, evidenced through increased topsoil cloddiness, were correlated with reduced crop yield. Although red ferrosols are considered to have excellent physical characteristics, and hence greater resilience to negative changes in soil condition compared to other soils exposed to similar intensive production practices, soil erosion, compaction and loss of organic matter are potential constraints to long-term productivity.

Comparatively little investigation has been made into the yield responses of vegetables to controlled traffic. Dickson et al. (1992) reported increases in total (14%) and marketable (18%) yield for potatoes grown under controlled traffic in Scotland, while Lamers et al. (1986) measured increases for ware (3%) and seed (7%) potatoes under controlled traffic in The Netherlands. Crops grown in a commercial seasonal CTF system in The Netherlands showed a variety of yield responses, ranging from no change to significant increases, such as 10% for onions and 35% for spinach (Vermeulen and Mosquera, 2009).

Adoption of controlled traffic in the Tasmanian vegetable industry is limited for a number of reasons, including the lack of compatible equipment across a diverse range of crops (McPhee and Aird, 2013), the influence of undulating topography (McPhee et al., 2013) and a lack of locally relevant experience. In addition, there is a lack of locally relevant research data to support adoption of CTF by the Tasmanian vegetable industry. This study was established to: (i) determine the effect of controlled traffic on soil physical properties in red ferrosols, specifically bulk density and penetration resistance (as indicators of soil compaction), (ii) evaluate the effect of adopting controlled traffic on the number of machinery operations for a range of economically important crops, and (iii) identify potential mechanical, logistical or agronomic barriers to adoption of controlled traffic systems within the Tasmanian vegetable sector. Seasonal CTF, in which all operations except harvest were confined to permanent traffic lanes, was initially used on one of the study sites due to the unavailability of compatible machinery for the harvest of the first crop. This situation reflects the broader challenges of controlled traffic adoption faced by the vegetable industry.

2. Materials and methods

2.1. Trial sites

Two field trials were established on red ferrosols (Isbell, 2002) in north-west Tasmania (950 + mm winter dominant annual rainfall) to evaluate the impact of controlled traffic on soil properties, machinery operations and crop production. A third non-replicated farm demonstration site was established on a brown dermosol (Isbell, 2002) in the northern midlands of Tasmania (620 + mm winter dominant annual rainfall), an area in which irrigated vegetable production is expanding. Properties of the soils at all sites are given in Table 1.

2.1.1. Site 1

Site 1 was in a mildly undulating field at the Tasmanian Institute of Agriculture Vegetable Research Facility, approximately 9 km west-south-west of Devonport, Tasmania (41°12′ 20″ S, 146°15′ 50″ E). Two treatments were imposed:

- controlled traffic (CTF) based on 2 m track gauge
- conventional practices (Conv) using random traffic and wheel track configurations appropriate to normal industry practice.

The experimental design featured two replications of the two treatments, with three evenly spaced sampling strips transecting the replicate × treatment plots. The spatial arrangement of all sampling sites was designed to permit paired site analysis (Fig. 1).

The controlled traffic treatment was established by deep ripping a short-term rye grass green manure crop using a tractor with RTK GNSS guidance controlled steering. Permanent wheel tracks were established by removal of the ripper tines behind the tractor tyres. Guidance was not used in the conventional area, and the soil was cultivated the full width of the ripper. The first crop was potatoes, but no soil measurements were taken. The potatoes in the CTF area were planted at the conventional row spacing of 81 cm within the 2 m track gauge, and harvested with a twin row harvester modified to a 2 m track gauge, outloading to a tractor-drawn chaser bin, also on 2 m track gauge. Harvest in the conventional area was done with an industry standard single row bunker harvester which did not conform to the 2 m track gauge. Potatoes were followed by a short-term rye grass green manure crop and then onions, which was the first vegetable crop used for the measurements reported here.

Crops over the 3 year trial period included onions, broccoli, beans, and processing carrots. Between beans and carrots, successive green manure crops of BQ mulch® (a proprietary mix of *Brassica spp.* which produces high biomass and bio-fumigant compounds) and rye grass were grown. The crop zone remained untrafficked throughout the trial, although mechanisation limitations meant the wheel tracks were not as well confined as desired. Both treatments were cultivated as required, although the type, number and intensity of tillage operations varied with the treatment and seedbed requirements. A record was kept of tillage operations.

2.1.2. Site 2

Site 2 was established in a steeply undulating 12 ha field on a commercial farm at Forth (41°12′ 43″ S, 146°16′ 28″ E), approximately 8 km west-south-west of Devonport, Tasmania. Two treatments, each with four replicates, were imposed within a randomized block design:

- seasonal controlled traffic (SCTF) based on 2 m track gauge, in which harvest was to be done using conventional, random traffic practices
- conventional practices (Conv) using random traffic and wheel track configurations appropriate to normal industry practice for all machinery operations.

At the outset, cultivation operations were common across both treatments, the only difference being the use of satellite guidance in the SCTF areas. As the trial progressed, it was possible to harvest some crops (e.g. winter broccoli, beans) using controlled traffic compatible harvest practices, and differences emerged in the type, number and intensity of tillage operations used in the two treatments. Crops grown over the three year trial were poppies, winter broccoli and beans, followed by a rye grass green manure crop. The final crop, leeks, was planted sequentially over a period of three months, with a harvest schedule spanning five months.

Table 1
Properties of soils from sites 1, 2 and 3.

	Site 1	Site 2	Site 3
Location	Forth, Tasmania (41°12′20″S 146°15′50″E)	Forth, Tasmania (41°12′43″S 146°16′28″E)	Cressy, Tasmania (41°39′S 147°04′40″E)
Australian soil classification	Red ferrosol	Red ferrosol	Brown dermosol
Great Soil Group	Krasnozem	Krasnozem	Podzol
A horizon			
Depth	0–25 cm	0–28 cm	0–30 cm
Texture	Clay loam	Clay loam	Clay loam
Colour	Dark reddish brown (2.5YR3/4)	Reddish brown (5YR5/4)	Dark brown (7.5YR3/2)
Structure	Moderately developed medium (20–50 mm) polyhedral	Moderately developed medium (20–50 mm) polyhedral	Moderately developed (20–50 mm) granular
pH (H_2O)	6.6	6	5
Organic carbon	3.6	4.1	2.6
B horizon			
Depth	25–91 cm	28–77 cm	30–45 cm
Texture	Clay loam	Light clay	Medium clay
Colour	Reddish brown (2.5YR4/3)	Dark reddish brown (5YR3/4)	Dark yellowish brown
Structure	Moderately developed (20–50 mm) angularblocky	Moderately developed medium (20–50 mm) polyhedral	Moderately developed (20–50 mm) angular blocky
pH (H_2O)	6.6	6	5.1
Organic carbon	3.1	3.2	1.3

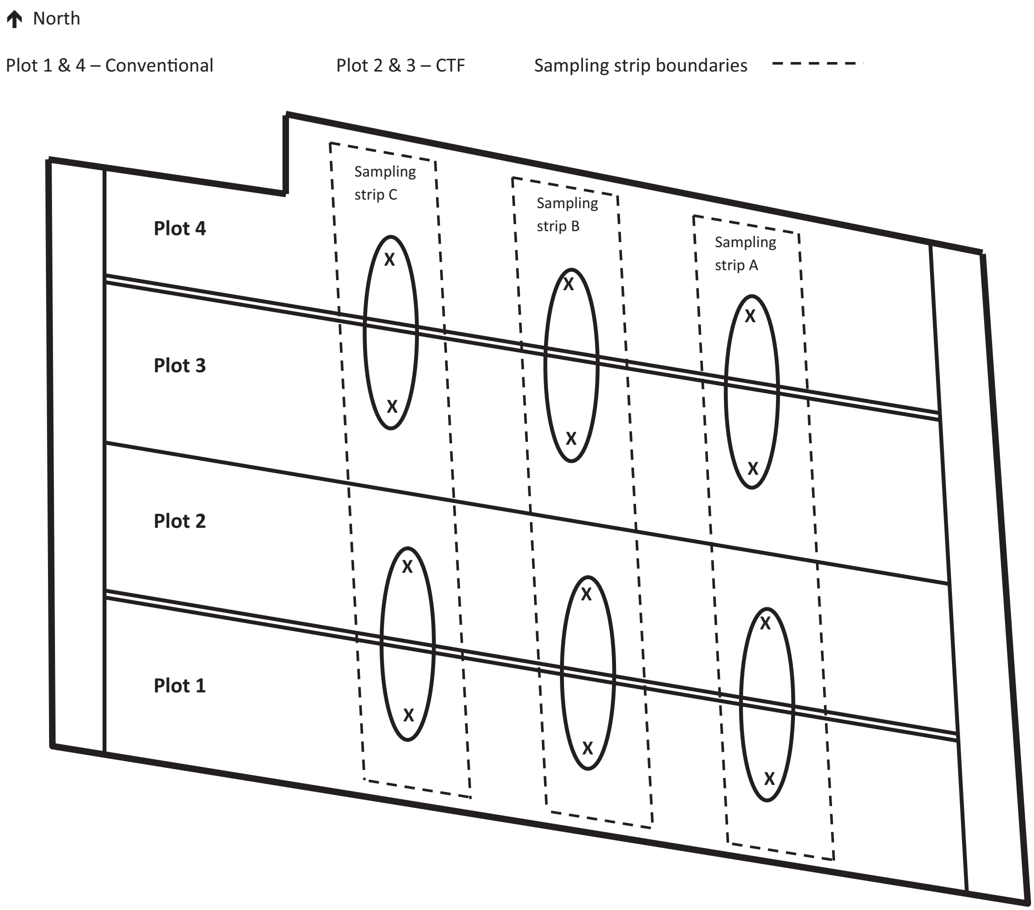

Fig. 1. Trial design for site 1 showing treatments and sampling strips. 'X' indicates the locations from which soil samples and soil resistance measurements were taken. The matched-pairs used for statistical analysis are indicated.

2.1.3. Site 3

Site 3 was established in a flat 3 ha field on a commercial farm approximately 4 km north of Cressy, Tasmania (41°39′ S, 147°04′ 40″ E). Two treatments were imposed as part of a non-replicated on-farm demonstration:

- controlled traffic (CTF) based on 2 m track gauge
- conventional practices (Conv) using random traffic and wheel track configurations appropriate to normal industry practice for all machinery operations.

Both treatments were cultivated as required, and a record was kept of tillage operations. Crops grown were potatoes and broccoli, each preceded by a rye grass green manure, over two cropping seasons.

At all sites, the adequacy of tillage operations in preparing a tilth suitable for crop establishment was judged by the relevant farm manager.

2.2. Soil measurements at sites 1 and 2

Bulk density was sampled using 70 mm diameter by 50 mm deep intact cores (McKenzie et al., 2002) at the mid-season of each cash crop. Core samples were taken at depths of 0–50, 125–175 and 275–325 mm, identified as 25 mm, 150 mm and 300 mm, respectively. At site 1, cores were taken from each sampling strip (Fig 1), whereas at site 2, only one location in each treatment was sampled. Bulk density (ρ_b) and volumetric water content (θ_v) were determined by gravimetric analysis 24–48 h after drying at 105 °C (McKenzie et al., 2002). Total (ϕ) and air-filled (ϕ_a) porosity were subsequently calculated, assuming a particle density of 2.65 g/cm^3. Air-filled porosity was calculated as the proportion of total porosity occupied by air given the moisture content at the time of sampling.

In the early phase of work at site 1, cores were also taken from both treatments following onion harvest and broccoli planting. This was to evaluate the impacts of random traffic during onion harvest in the Conv treatment, and the capacity of tillage under a random traffic system to remediate and maintain a loosened soil state until after broccoli planting. In the latter phases of work at site 2, dates of sampling varied due to the sequential leek planting schedule, but sampling times were retained at the mid-season date for each planting.

Soil penetration resistance data were collected at site 1 using a Rimik® CP-20 recording cone penetrometer at the same time the bulk density cores were collected. Insertions were made at 100 mm intervals along a 2.5 m transect in each sampling strip (Fig 1), to a depth of 600 mm, with resistance force automatically recorded at 15 mm increments. The 2.5 m transect allowed inclusion of a full crop bed bounded by adjacent wheel tracks. Soil penetration resistance data were analysed to determine treatment differences, and also used to generate profiles of transects across beds and wheel tracks as an illustrative extension tool.

Infiltration rate was measured at site 1 in winter 2010 and spring 2011 using a Cornell sprinkle infiltrometer (Ogden et al., 1997) with a single 241 mm diameter infiltration ring. The average maximum application rate of the infiltrometer varied from 180–190 mm/h over the two tests. Data were recorded every three minutes, and volumetric soil moisture determined pre- and post-test by intact cores. Measurements were replicated twice with the tests conducted at the sites indicated in sampling strip B (Fig. 1).

Statistical analyses of soil physical data were performed using SAS 9.3 (SAS Institute Inc., Cory, NC, USA). For site 1 soil properties, matched-pair *t*-tests were used to analyse the data where matching was identified in advance on the basis of plot adjacency. Site 2 soil properties data, and site 1 infiltration data, were analysed using an ANOVA mixed modelling approach assuming a randomised complete block design. At site 1 there were 2 blocks, each containing 2 plots, and at site 2 there were 4 blocks each containing 2 plots.

Examination of plotted data indicated a change in the trend in penetration resistance above and below 300 mm (the nominal depth of ripping) at site 1. Therefore, we fitted a segmented linear model consisting of two cubic polynomials (Draper and Smith, 1981).

The model is shown below, in which t represents treatment (CTF, Conv); CP is the estimated cone penetrometer soil resistance; I_t is the model intercept; α_t is a linear effect for $y > p$; β_t is a quadratic effect for $y < p$; γ_t is a cubic effect for $y < p$; δ_t,ε_t, and ζ_t are the same effects for $y \geq p$; and W_t is the 'jump' that occurs at the cut point $y = p$, where y is the depth and p is the cut point.

$$CP = \begin{cases} I_t + \alpha_t y + \beta_t y^2 + \gamma_t y^3 & \text{if} y < p \\ I_t + W_t + \delta_t y + \varepsilon_t y^2 + \zeta_t y^3 & \text{if} y \geq p \end{cases}$$

We fitted the model assuming Matérn spatial correlation structures except for carrots where the spherical structure was used. Differences between treatments were obtained by calculating polynomial contrasts at each depth. The P values for the differences were adjusted for multiplicity by simulation (Westfall et al., 2011). All analyses were done using Proc Mixed and Proc PLM in the SAS System, version 9.3.

2.3. Tillage operations

Details of cultivation operations (number and type) were noted for each crop and each traffic treatment. As the work largely relied on currently available equipment, CTF and SCTF treatments were mostly cultivated using the same or similar equipment to that used in the Conv treatments. Exceptions were:

- the exclusion of mouldboard ploughing from CTF treatments, due to its incompatibility with the need to preserve permanent wheel tracks
- the use of a ripper with most tynes removed to undertake edge ripping of the CTF beds to deal with encroaching wheel compaction, compared to a full width ripper used in the Conv and SCTF treatments
- the use of a prototype wavy disc cultivator in the final season of CTF work at site 3.

Decisions on timing of operations were made by experienced operators in accordance with commercial considerations regarding seeding dates or other time critical requirements.

2.4. Crop yield

Hand harvests were taken at site 1 to determined crop yield. Samples were taken from each of the sampling strip locations indicated in Fig. 1. Matched-pair *t*-tests were used to analyse the data where matching was identified in advance on the basis of plot adjacency. Commercial harvest yields were obtained for site 2, with harvested crop separated on the basis of treatments and replications.

3. Results

3.1. Bulk density

Significant differences ($p < 0.05$) in soil bulk density (ρ_b), occurred in 8 of the 18 soil depth by crop combinations at site 1 (Table 2), with an additional two instances indicating similar trends ($p < 0.1$). At least one significant difference occurred between treatments for at least one soil depth in each cropping season, and all but one depth by crop combination (carrots Jan 2012, 300 mm) showed a reduced bulk density under the CTF treatment. Out of the six crops grown at site 1, bulk density was significantly reduced in CTF for onions (Mar 2010) and broccoli (May 2010) at 25 mm depth, onions (Dec 2009 and Mar 2010) and broccoli (May 2010) at 150 mm depth, and broccoli (Jul 2010) and beans (Dec 2010) at 300 mm depth. Significant reductions in bulk density were most evident at 150 mm depth on the first three sampling occasions, with a somewhat weaker response ($p = 0.06$) on the fourth occasion. At 300 mm depth, evidence of reduced bulk density was weak ($p = 0.06$) on the second sampling, and stronger later in the cropping cycle.

At site 2, significant differences in bulk density between treatments occurred in only one season (beans 2012) out of four and only at the 150 mm depth, at which time the bulk density under SCTF was significantly lower ($p < 0.01$) than under the Conv treatment (Table 3). This occurred after two seasons of CTF management on the site, which was possible due to the selection of crops which could be harvested with CTF compatible machinery.

Table 2
Results for bulk density (ρ_b), volumetric water content (θ_v), total porosity (φ) and air filled porosity (φ_a) for controlled traffic and conventional treatments at three depths across a number of cropping seasons at site 1. Significant differences resulting from *t*-tests are shown as *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, and + = $p < 0.1$.

Depth (mm)	Soil property	Onions (Dec 09)			Onions (Mar 10)			Broccoli (May 10)			Broccoli (Jul 10)			Beans (Dec 10)			Carrots (Jan 12)		
		onv	CTF	p	Conv	CTF	p	Conv	CTF	p	Conv	CTF	p	Conv	CTF	p	Conv	CTF	p
25	ρ_b (g/cm^3)	0.98	1.01	ns	1.06	0.91	**	1.00	0.91	***	1.00	0.97	ns	1.18	1.14	ns	1.05	1.02	ns
	θ_v (%)	28.9	27.4	ns	33.5	28.6	**	31.9	26.7	***	42.1	39.4	ns	28.3	25	**	23.2	24	ns
	φ (%)	63	62.1	ns	60	65.7	**	62.4	65.8	***	62.2	63.2	ns	55.6	57	ns	60.5	61.7	ns
	φ_a (%)	34.1	34.7	ns	26.6	37.2	**	30.5	39.1	***	20	23.8	ns	27.3	32	*	37.3	37.7	ns
150	ρ_b (g/cm^3)	1.2	1.04	**	1.22	1	***	1.13	1.01	*	1.12	1.02	+	1.28	1.22	ns	1.08	1.15	ns
	θ_v (%)	44.5	38.4	**	43.6	35.5	***	41.8	37.5	ns	44.9	40.1	*	40.3	36.3	+	29.8	30.1	ns
	φ (%)	54.8	60.9	**	54	62.2	***	57.2	62.1	*	57.7	61.4	+	51.6	54	ns	59.4	56.6	ns
	φ_a (%)	10.3	22.5	**	10.4	26.7	***	15.4	24.6	+	12.7	21.3	*	11.3	17.7	+	29.6	26.5	ns
300	ρ_b (g/cm^3)	1.12	1.12	ns	1.17	1.08	+	1.11	1.05	ns	1.16	1.09	*	1.32	1.2	*	1.12	1.24	*
	θ_v (%)	41.1	40.2	ns	42.3	38.2	*	42	38.5	ns	44.8	40.8	**	36.4	33.4	ns	31.1	30.8	ns
	φ (%)	57.6	57.7	ns	55.7	59.4	+	58.1	60.4	ns	56.2	58.8	*	50.1	54.7	*	57.7	53.4	*
	φ_a (%)	16.5	17.6	ns	13.4	21.2	*	16.1	21.9	ns	11.4	18	**	13.7	21.3	*	26.6	22.6	+

3.2. Volumetric water content

Eight of the 18 soil depth by crop combinations at site 1 showed significant ($p < 0.05$) reductions in volumetric water content (θ_v) due to CTF, with one other occasion showing a similar trend ($p < 0.1$) (Table 2). Significant differences occurred on three occasions at 25 mm (Mar, May and Dec 2010) and 150 mm (Dec 2009, Mar and Jul 2010), and twice at 300 mm (Mar and Jul 2010). Significant differences were observed on two occasions at site 2, once at 25 mm depth (Dec 2010), and once at 150 mm depth (Jan 2012), where once again, the CTF treatment led to lower volumetric water content (Table 3).

3.3. Air-filled Porosity

At site 1, CTF management significantly ($p < 0.05$) increased air-filled porosity in nine of the 18 sampling depth by crop combinations (Table 2). At site 2, the only significant differences in air-filled porosity existed at 25 and 150 mm depths in the third season (Jan 2012), when air-filled porosity was higher under SCTF (Table 3).

3.4. Soil resistance

Significant differences in penetration resistance occurred for all crops except carrots at site 1, although the proportion of the depth profile at which differences occurred diminished over time. The greatest number of significant differences existed at the first sampling time (Dec 2009) and occurred from 50 mm to 400 mm depth (Fig. 2(a)). In keeping with other data, such as bulk density, by Jan 2012 (carrots) the differences in soil resistance between treatments had disappeared (Fig 2(f)).

Fig. 3 shows example transect plots illustrating the lower strength conditions within the CTF beds, the higher strength in the CTF wheel tracks, and the generally more random distribution of soil strength in the Conv treatment.

3.5. Infiltration

Precise determination of the infiltration rate was limited by the maximum output (approximately 180–190 mm/h) of the sprinkle infiltrometer. In broccoli 2010, the average infiltration rate in the CTF treatment was >180 mm/h, compared to 3 mm/h in the Conv treatment, which exhibited runoff after only 2.2 min (Table 4). The second test (August 2011) was conducted soon after the soil had been cultivated, and the infiltration rate was in excess of 180 mm/h, with no run-off generated from either treatment.

3.6. Tillage operations

At all three sites, CTF reduced the number of tillage operations required to form a seedbed, although considerable differences existed between sites due to differences in soil type (sites 1 and 2, compared to site 3) and crop requirements. At site 1, CTF required a total of six tillage operations compared to 12 for the Conv treatment (Table 5) over the full cropping cycle. The differences arose through the CTF treatment requiring fewer power harrow, and no mouldboard plough, operations. Site 2 (Table 6) showed a difference of only 3 operations between the treatments (SCTF – 12, compared to Conv – 15). The types of tillage operations used were common between treatments up until the final season. Site 3 showed the greatest difference in tillage operations between treatments, with 6 operations for CTF, and 14 for Conv (Table 7). Fig 4. illustrates the site 3 soil conditions at the time of broccoli planting following tillage operations as described in the green manure–broccoli transition in Table 7.

3.7. Crop yield

The only season to demonstrate any difference in crop yield at site 1 was the first, in which there was a significant improvement in marketable onion yield for the CTF treatment. No significant differences in yield were measured at site 2. Marketable yield differences for sites 1 and 2 are shown relative to the Conv treatment (Table 8).

4. Discussion

4.1. Bulk density, volumetric water content and porosity

Field trials demonstrated that controlled traffic has the potential to reduce soil bulk density and volumetric water content, and increase air-filled porosity in Tasmanian vegetable production systems. However, soil responses to CTF differed between sites, crops and soil depth, and in some cases reversed as the cropping cycle progressed, due to limitations associated with current mechanisation and tillage systems. For example, reliance on conventional tillage equipment no doubt caused more soil disturbance than was actually required on most occasions in the CTF treatments. The capacity to maintain the soil benefits gained from controlled traffic may be limited without further modification to management practices. For example, at site 1, Jan 2012, differences in soil properties between treatments at the time of the previous crop had disappeared at 25 mm and 150 mm depths, and had reversed at 300 mm (Table 2). The exact cause of these changes is not known, but is thought to be due to differences in tillage operations between the two treatments, and the need to manage

Table 3
Results for bulk density (ρ_b), volumetric water content (θ_v), total porosity (φ) and air filled porosity(φ_a) forcontrolled traffic and conventional treatments at three depths across a number of cropping seasons at site 2. Significant differences resulting from ANOVA are shown as *** =$p < 0.001$, ** =$p < 0.01$, * =$p < 0.05$, and + =$p < 0.1$.

Depth (mm)	Soil property	Poppies (Dec 10)			Broccoli (Jul 11)			Beans (Jan 12)			Leeks (Mar–Jun 13)		
		Conv	SCTF	p	Conv	SCTF	p	Conv	SCTF	p	Conv	SCTF	p
25	ρ_b (g/cm^3)	1.03	1.08	ns	0.98	0.97	ns	1.08	1.01	ns	0.96	0.95	ns
	θ_v (%)	21.9	20.1	*	29.2	28.1	ns	16.8	15.3	ns	24.7	24.8	ns
	φ (%)	61.1	59.1	ns	63	63.4	ns	59.3	62	ns	63.6	64.1	ns
	φ_a (%)	39.3	39	ns	33.8	35.3	ns	42.5	46.7	*	38.9	39.3	ns
150	ρ_b (g/cm^3)	1.14	1.21	ns	1.1	1.08	ns	1.21	1.01	**	1.14	1.03	ns
	θ_v (%)	30.7	26.5	ns	36.1	34.6	ns	27.4	22.8	**	29.8	32.2	ns
	φ (%)	57.1	54.2	ns	58.4	59.2	ns	54.5	62.1	**	57.1	61.3	ns
	φ_a (%)	26.3	27.7	ns	22.3	24.6	ns	27.1	39.2	**	27.3	29.1	ns
300	ρ_b (g/cm^3)	1.2	1.35	ns	1.19	1.12	ns	1.22	1.2	ns	1.27	1.21	ns
	θ_v (%)	27.4	31	ns	38.3	35.8	ns	29.2	30	ns	32.3	31.6	ns
	φ (%)	54.7	49	ns	55.1	57.8	ns	53.9	54.7	ns	52	54.4	ns
	φ_a (%)	27.7	18	ns	16.8	22	ns	24.7	24.7	ns	19.6	22.7	ns

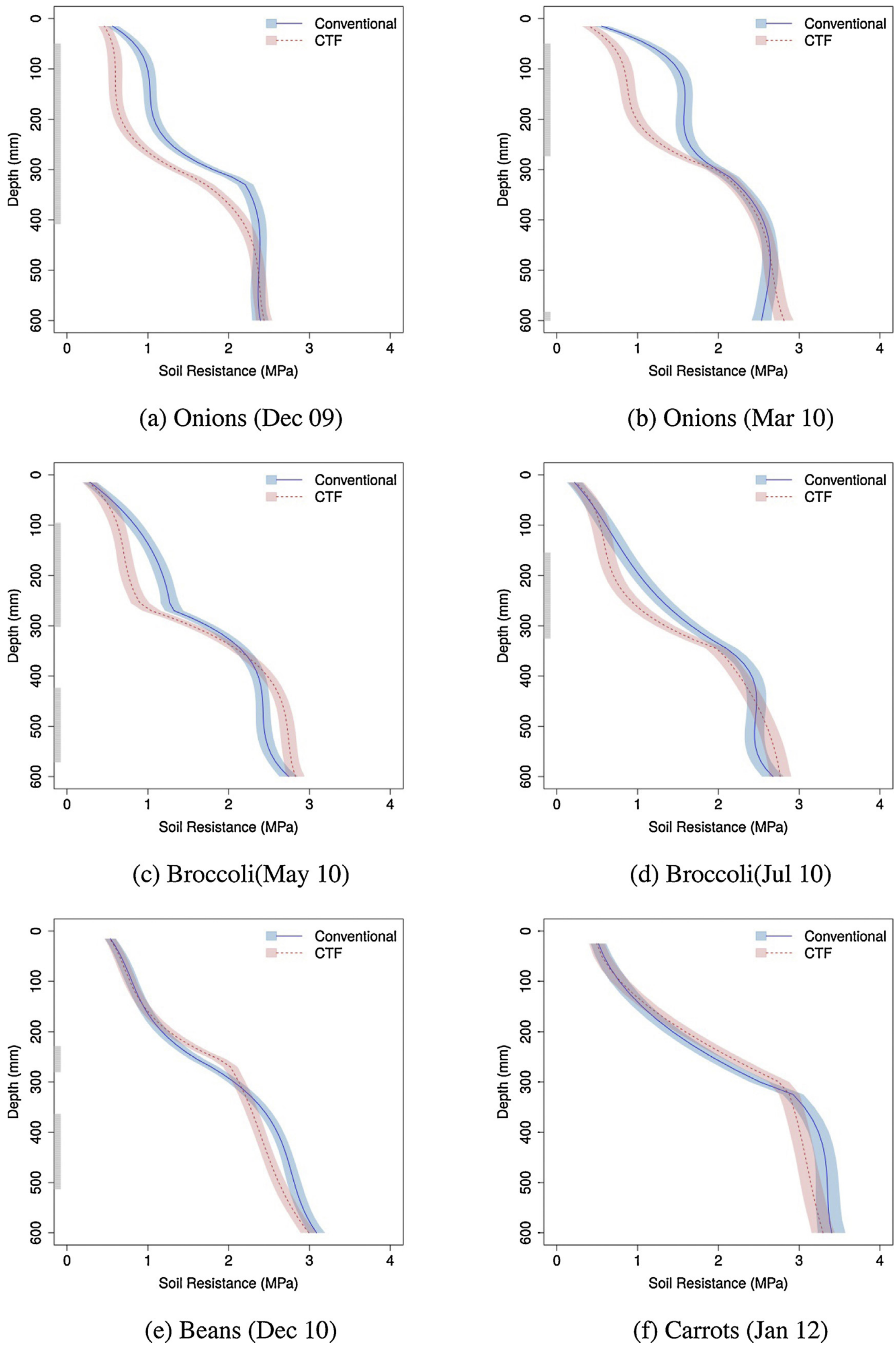

Fig. 2. (a–f) soil resistance profiles from six sampling times at site 1. All profiles extend to 600 mm deep, soil resistance in MPa. Grey bars on the depth axis indicate those zones of the profile for which there are significant differences between treatments ($p < 0.05$). The bands on the resistance curves represent the 95% CI.

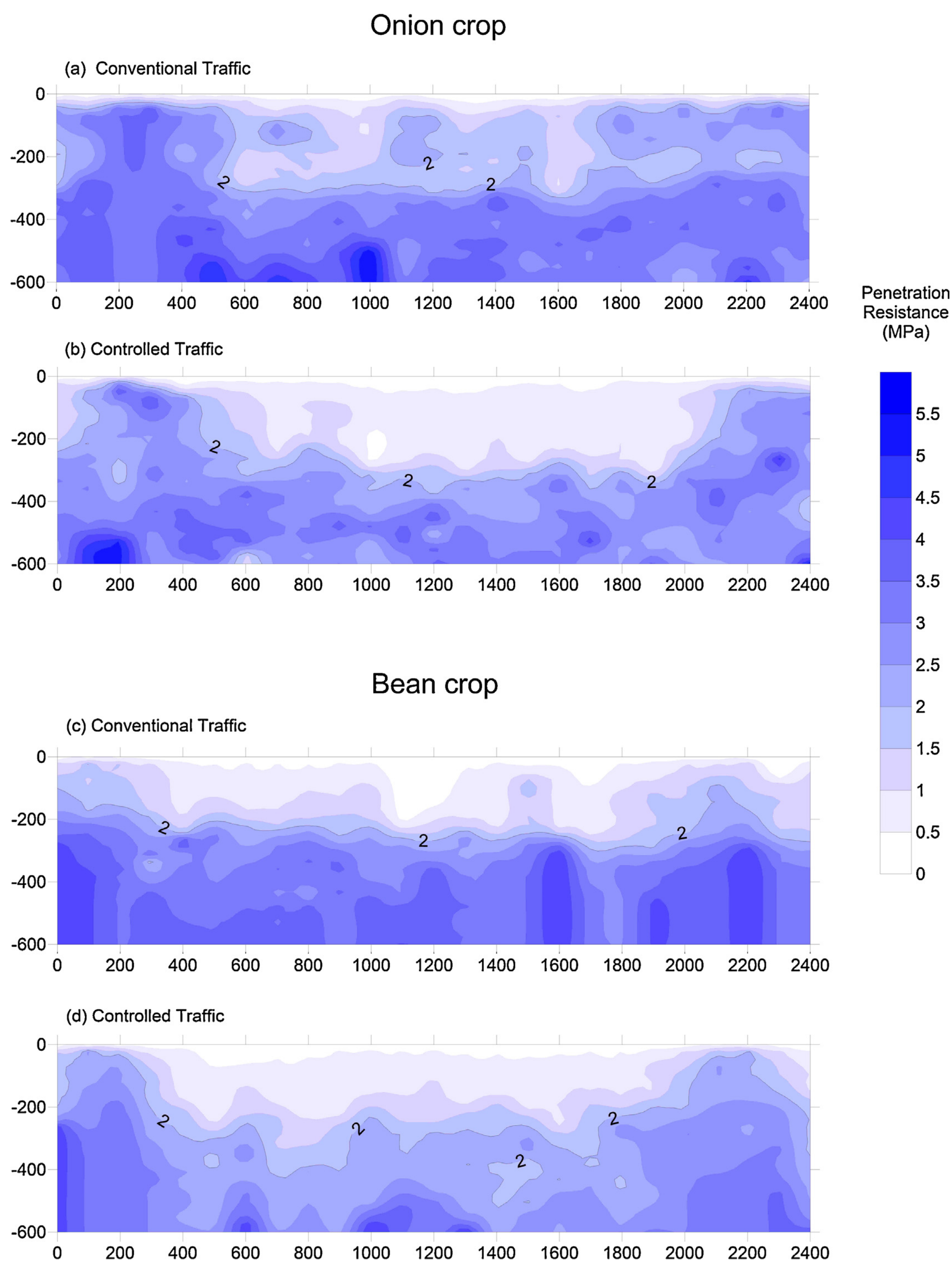

Fig. 3. Soil resistance transects from Conv (a, c) and CTF (b, d) treatments after onion harvest (top) and during the growing season of beans (bottom) at site 1. Legend, with resistance values in MPa, appears at right. The 2 MPa contour is indicated on each transect. The wheel track centres in the CTF transects are approximated by the 200 mm and 2200 mm points on the *x*-axis.

Table 4
Data from two infiltration tests at site 1.

	Broccoli (Jul 2010)		Cultivated (Aug 2011)	
	Conv	CTF	Conv	CTF
Duration of test (min)	30	90	90	90
Infiltration rate (mm/h)	3	Exceeded output	Exceeded output	Exceeded output
Time to initial run-off (min)	2.2	Not reached	Not reached	Not reached
Time to steady state run-off (min)	6	Not reached	Not reached	Not reached

Table 5
Type and number of tillage operations completed with each cropping season transition under Conv and CTF systems, site 1.

	CTF		Conventional	
	Tillage operations[a]		Tillage operations	
Crop transition	Type	Number	Type	Number
Potatoes–rye grass–onions	• Bed rip • Power harrow bed reform, sow rye grass	2	• Rip • Power harrow bed form, sow rye grass • Power harrow	3
Onions–broccoli	• Bed edge rip[b]/ roll	1	• Rip • Power harrow • Power harrow bed formation	3
Broccoli–beans	• Rotary hoe	1	• Rotary hoe • Rip • Power harrow	3
Beans–BQ mulch[c]–rye grass–carrots	• Rip • Rotary hoe[d]	2	• Plough • Rotary hoe • Power harrow	3
Total number of operations		6		12
% Reduction for CTF		50		

[a] Unless otherwise noted, nominal depths of tillage for all operations at all sites were as follows: rip – 300 mm, power harrow – 150 mm, plough – 250 mm, rotary hoe – 100 mm.
[b] On some occasions, ripping was required only at the interface between the edge of the track and the bed, to remediate soil compaction which had encroached on the bed due to wide tyres.
[c] A proprietary mix of Brassica spp.which produce high biomass and bio-fumigant compounds (ref http://www.pggwrightsonseeds.com.au/products/brassica/bioquremixes/bioquremulch/).
[d] Nominal depth of tillage for rotary hoe prior to carrots was 150 mm.

excess green manure crop biomass in the CTF treatment just prior to seeding.

Overall, evidence from the field trials demonstrates improved soil physical conditions under CTF management, specifically from the data of Mar and May 2010 at site 1, and Jan 2012 at site 2. At site 1, Mar 2010 data represent the differences arising from random and controlled harvest traffic on the Conv and CTF treatments, respectively. Subsequent tillage operations, undertaken to remediate the impact of onion harvest traffic, were much the same, except that the Conv treatment received one more power harrow operation. Measurement of soil properties in the early stages of the subsequent broccoli crop (May 2010) showed significant differences in some soil properties at the 25 and 150 mm depths, indicating that tillage after random traffic could not remediate compacted soil to the same conditions achieved when compaction was avoided with the use of controlled traffic.

The second example of improved soil physical conditions under CTF management is seen in the data from site 2, Jan 2012. The first crop at this site was managed with SCTF, due to there being no CTF-compatible poppy harvester available. Differences in soil properties only occurred in Jan 2012 after two seasons of fully integrated controlled traffic. Tillage practices were the same for both treatments up to this time, indicating that the isolation of traffic from the crop zone was a major factor contributing to the differences in soil properties.

McHugh et al. (2009) showed that isolation of traffic in zero-till grain production was sufficient for natural soil processes and root growth to bring about improvements in structure in a self-mulching soil. However, none of the vegetable crops grown in this work were established using zero-till. Tillage is extensively used in vegetable production systems to remediate the impacts of soil compaction and manage surface residues. As the systems studied in this work were in the early stages of development, some remedial tillage was required to deal with encroaching traffic compaction, particularly at the bed-track interface. Tillage for residue management was required as zero-till capable vegetable seeders were not available. The results presented here suggest that isolation of traffic can provide benefits for soil physical conditions, even in the presence of high disturbance conventional tillage operations. This assessment is supported by the work of Lamers et al. (1986), who showed that using controlled traffic for vegetable production, in conjunction with conventional tillage, gave significant increases in total porosity (4%) compared to fields with normal traffic. However, maintenance of the benefits requires more than just traffic management, and must also take into account the changed tillage needs of a controlled traffic system. For example, with the isolation of traffic from the crop zone, it should be possible to restrict tillage to residue management operations, and perhaps strip tillage in some circumstances. The volume of soil disturbed in such altered tillage operations should be considerably reduced, and hence minimise some of the negative impacts associated with tillage in intensive vegetable cropping, such as declining organic carbon and structural decline (Cotching et al., 2001, 2013; Sparrow et al., 1999, 2013).

When statistical differences occurred, volumetric water content in the CTF treatment was 9–19% lower than the Conv treatment at site 1, and 8–17% lower at site 2. Similar results have been observed in controlled traffic based on raised beds (Holland et al., 2008). The results may indicate the reduced soil density under controlled traffic led to increased gravitational drainage, compared to the conventional treatment. However, lower moisture could have also resulted from a number of mechanisms related to soil, water and crop interactions. More research is required to resolve the influence of CTF on pore size distribution, not just total porosity. These results suggest an increased likelihood of higher soil moisture in conventionally managed soils. This has consequences for the impact of random traffic on these soils, as higher moisture content makes soils, particularly those with high clay content, more susceptible to compaction damage (Hamza et al., 2011; Nawaz et al., 2013).

Plant growth may suffer in soils with low air-filled porosity. As reported in Wesseling (1974), various researchers in the 1950s and

Table 6
Type and number of operations completed with each cropping season transition under Conv and SCTF systems, site 2.

	SCTF		Conventional	
	Tillage operations		Tillage operations	
Crop transition	Type	Number	Type	Number
Fallow–poppies	• Rip/rotary hoe • Powerharrow/seed	2	• Rip/rotary hoe • Power harrow/seed	2
Poppies–broccoli	• Rotary hoe • Rip • Powerharrow	3	• Rotary hoe • Rip • Power harrow	3
Broccoli–beans	• Rip/rotary hoe • Powerharrow	2	• Rip/rotary hoe • Power harrow	2
Beans–green manure	• Rotary hoe • Rip	2	• Rotary hoe • Rip	2
Green manure–leeks	• Rip • Rotary hoe • Power harrow bed refurbishment	3	• Multi-disc[a] • Plough • Power harrow • Power harrow • Rip • Power harrow	6
Total number of operations		12		15
% Reduction for CTF		20		

[a] Nominal depth of tillage for multi-disc – 50 mm.

1960s proposed lower limits of air-filled porosity for plant growth ranging from 10–20%. A critical level of 10% appears to be widely accepted in more recent literature (Hakansson and Lipiec, 2000; Lipiec and Hakansson, 2000). Across the range of sampling depths and times, air-filled porosity at the time of sampling was significantly different between treatments on a number of occasions, although never below 10%. However, there were occasions at site 1 (e.g. 150 mm–Dec 09, Mar 10; 300 mm–Jul 10) (Table 2) when air-filled porosity in the Conv treatment was only marginally greater than 10%, while under CTF, it was 1.5–2.5 times higher. Significant differences occurred twice at site 2 (25 and 150 mm depth in Jan 2012), but all measurements were well above 10%. While the air-filled porosity was never below 10% at the times of measurement, the large differences between the treatments point to the capacity of controlled traffic to substantially reduce the risk of plant growth being negatively impacted by saturated soil conditions.

4.2. Soil resistance

Differences in soil penetration resistance were most apparent early in the cropping rotation, with significant differences between

Table 7
Type and number of tillage operations completed with each cropping season transition under Conv and CTFsystems, site 3.

	CTF		Conventional	
	Tillage operations		Tillage operations	
Crop transition	Type	Number	Type	Number
Green manure–potatoes	• Rip in line with bed • Power harrow bed form	2	• Cross-rip × 2 • Power harrow bed form	3
Potatoes–green manure	• Rip in line with bed • Power harrow bed form	2	• Cross-rip × 2 • Offset disc[a] • Power harrow bed form	4
Green manure–broccoli	• Wavy disc surface tillage[a]	1	• Cross-rip × 2 • Offset disc • Power harrow bed form	4
Broccoli–green manure	• Wavy disc surface tillage	1	• Offset disc × 2 • Power harrow bed form	3
Total number of operations		6		14
% Reduction for CTF		57		

[a] Nominal depth of tillage for wavy disc – 50 mm and offset disc – 150 mm.

the two treatments during and after the onion crop. While significant differences were measured in all but the last season, the proportion of the profile exhibiting differences declined over time. At the time of collecting the second broccoli data (Jul 2010), the soil profile was very wet from winter rainfall, which may have made it more difficult to detect differences in resistance, particularly in the upper soil layers. However, below 200 mm depth, the resistance in the CTF beds was significantly lower than that in the Conv treatment. This is consistent with other soil physical data, such as bulk density (Table 2).

Data from the bean crop (Dec 2010) shows a deeper zone with no differences, possibly due to differences in the preceding tillage regime. The only tillage implement used on the CTF beds was a rotary hoe to manage residue from the broccoli crop, whereas the Conv area received three tillage operations, one of which was ripping. This would have reduced soil resistance in the tillage zone of the Conv treatment. Interestingly, resistance in most of the CTF tillage zone was not significantly different from the ripped soil in the Conv treatment, despite not being ripped. The absence of differences in soil resistance in the carrot crop (Jan 2012) was most likely due to the tillage regime which was required to manage the excess biomass from the preceding green manure crops.

4.3. Infiltration

The two infiltration tests were conducted under very different antecedent soil moisture conditions, with the Aug 2011 conditions being much drier than those of Jul 2010. The large difference in infiltration rate between treatments in the wet soil conditions of Jul 2010 shows a major effect of CTF. Maintaining a high infiltration rate has a number of benefits for the management and sustainability of cropping. Soil with a high infiltration rate can cope with intense and/or protracted rainfall events, allowing more water to be stored in the soil, at the same time generating less run-off, and reducing the risk of erosion (Tullberg et al., 2001; Wang et al., 2008). This is particularly important in tillage-based cropping systems which do not retain sufficient residue cover to help control erosion, as is the case in most vegetable cropping scenarios.

4.4. Tillage operations and timeliness

In theory, soil managed with controlled traffic should not require tillage to remediate compaction. However, issues of tracking accuracy related to topography and machine operational considerations meant that remedial ripping operations were required in the CTF treatment. At site 1, compaction remediation tillage was largely confined to the interface between wheel tracks and the edge of the crop bed. As there was no need for broadscale deep ripping of the crop zone, there were fewer primary tillage operations, and they were of lower intensity. At site 2, tillage was managed in a more conventional fashion up until after the bean crop, with changes in the number of tillage operations only becoming apparent later in the cropping rotation. Ripping operations early in the cropping cycle where conducted across the full width of the bed at site 3. This was not required for remediation of traffic compaction, but based on the operator's view that natural consolidation of the soil needed to be relieved. Later in the cropping cycle, ripping was not used in the CTF treatment and hallow tillage with a wavy disc implement provided adequate conditions for transplanting (Fig. 4).

Table 8
Relative marketable yield of crops grown under CTF/SCTF (conventional system = 100) at two sites in north-west Tasmania.

Site	Crop	2010	2011	2012
1	Onion	114*		
	Broccoli	90		
	Beans		104	
	Carrots			86
2	Poppies		99	
	Broccoli		124	
	Beans			95

* Yield increase significant compared to conventional system ($p < 0.05$).

Reducing the number of tillage operations has been shown to provide several benefits. Firstly, tillage energy requirements are reduced, through both a reduction in the number of operations, and because tillage operations tend to be lighter draft and faster under controlled traffic (McPhee et al., 1995a). Secondly, fewer tillage operations will usually mean improved timeliness when transitioning from harvest of one crop to sowing of the next (McPhee et al., 1995b). For example, although sowing dates at all sites were constrained by other factors, such as contractual requirements, the CTF treatment at site 1 was ready for sowing 28, 2 and 3 days earlier than the conventional treatment for onions, broccoli and beans, respectively.

4.5. Yield

It is clear the influence of controlled traffic on crop yield is variable, with results indicating no change for a number of crops, and onions at site 1 showing a significant increase. The relatively low yield from the CTF carrot crop at site 1 (although not statistically different) is believed to have been due to the impacts of tillage operations described previously. While yield data for the broccoli crop at site 2 suggest a substantial increase under controlled traffic, the result was not statistically significant due to a large degree of variability both between treatments and within replicates.

It is perhaps not surprising that the yield responses are variable. Experience in other industries suggests it can take several seasons for soil improvements arising from controlled traffic to be reflected in crop quality and yield. Further, it is clear from the experiences of this study, that maintenance of CTF-induced soil benefits under current vegetable cropping systems is challenging due to mechanisation limitations. Therefore, it is expected that it would take even longer for consistent changes in yield response to occur. In addition, while soil management and seeding practices for conventional vegetable production have been refined over many decades, different approaches to accommodate the soil conditions which occur under controlled traffic require development.

5. Conclusion

The results of this study demonstrate that CTF can provide a number of benefits in vegetable cropping systems, although development of the system has not reached the point where these benefits can be maintained in the long-term. One of the principle advantages illustrated was the reduction in the number of tillage operations. The effect of CTF on soil physical properties was apparent through beneficial changes in soil bulk density, infiltration and soil resistance. However, results varied between sites, depths and crops, reflecting the limitations of current harvest operations, which compromise the non-trafficked beds as a result of mis-matched track gauge and working widths on machinery.

Experience in the grain industry suggests that the soil-related benefits of CTF tend to accrue and amplify over time. The use of similar equipment and practices over a wide variety of crops means it is much easier to maintain controlled traffic in the grain industry compared to the vegetable industry.

Although current tillage practices in the vegetable industry seek to remediate traffic induced soil compaction, the results reported here show a consistent trend for improved soil physical conditions

Fig. 4. Appearance of the soil surface at the time of broccoli planting at site 3 for the Conv treatment after four intensive tillage operations (left), and CTF treatment after one shallow surface tillage operation (right).

under controlled traffic, even with regular disturbance by tillage. Even though there is a level of variation in the results at site 1, all seasons except the last demonstrated some statistical improvement in soil physical conditions. Although statistical improvements were shown on only one occasion at site 2, this occurred after two seasons of controlled traffic, and in the presence of a conventional tillage regime. In addition, over the course of several crops, fewer operations were required for seedbed preparation at each site.

A large body of research has been reported over many years on the impacts of tillage on soil condition, and ways to reduce the negative impacts of tillage. While poorly managed tillage can seriously degrade soil physical properties in any cropping system, the work reported here, and from other researchers, reinforces the fact that traffic is actually the underlying problem. Without traffic compaction, the need for tillage, and the risk of tillage-induced soil degradation, is significantly reduced.

While some benefits can be gained from the partial use of controlled traffic, the Tasmanian vegetable industry will observe limited and inconsistent benefits until key mechanisation issues, such as track gauge and working width standardisation, and changes to tillage regimes to capitalise on the absence of compaction, are resolved.

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Soil arthropod responses to controlled traffic in vegetable production

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ABSTRACT

In this study, the effects of a controlled traffic (CT) management system on the soil arthropod assemblage in a Red Ferrosol (krasnozem) soil in north-west Tasmania were examined. Individual soil cores were collected at three depths over two seasons (winter and spring, 17 months apart), and soil fauna extracted using Berlese-Tullgren funnels. All arthropods were identified to the level of order and counted. Data were analysed to assess the effects of a controlled traffic system on the overall abundance and ordinal richness of the arthropod assemblage, as well as abundance and species richness in the collembolan assemblage. Multivariate analysis was used to examine the differences in the ordinal composition of the arthropod assemblage. The data were variable between seasons, with significant increases in arthropod and collembolan abundance ($p < 0.01$) at all depths being evident under controlled traffic in spring. Arthropod richness was significantly greater in spring ($p < 0.1$), but a similar effect was not measured for collembolan richness. Overall arthropod abundance was greater under CT in winter ($p < 0.1$), although by depth, differences between treatments were evident only in the deepest samples for arthropod abundance ($p < 0.05$) and arthropod and collembolan richness ($p < 0.1$). While it was not possible to separate the relative impacts of traffic and tillage, it is concluded that the controlled traffic system had positive effects on the abundance and diversity of soil arthropods.

1. Introduction

Agricultural soils retain many of the biological characteristics of natural soil ecosystems, despite the severe disturbance associated with cultivation, modification of vegetation and inputs of various agricultural chemicals. The biota of both agricultural and natural soil ecosystems almost universally include the root systems of higher plants, an abundant microflora of bacteria and fungi, and fauna such as protozoa, nematodes, arthropods and earthworms. To a substantial extent, the living component of agricultural soils has been ignored in agricultural systems, except for the management of a small number of pest and disease organisms (Crossley et al., 1992). Some effort has been made to understand the role of soil organisms in maintaining the physical structure and chemical fertility of soils, and these effects are proving to be overwhelmingly positive (Coleman and Whitman, 2005; Crossley et al., 1992; Lee and Pankhurst, 1992). A key challenge in agriculture is how to manage soils in ways which minimise the negative impacts on soil flora and fauna (Altieri, 1999).

In mechanised crop production, machinery is required for incorporation of crop residues, seed bed preparation, planting, weed control, irrigation, application of fertilizers, herbicides and pesticides and harvesting operations. One consequence of machinery traffic is soil compaction, while another is soil disturbance caused by the need for remedial tillage. The negative effects of soil compaction include reduced water infiltration, increased surface runoff and erosion, reduced soil aeration and gas exchange and reduced crop growth (Batey, 2009; Chamen et al., 1992; Hakansson et al., 1988; Hamza and Anderson, 2005). One of the key reasons for tillage in vegetable production is for the remediation of soil compaction to create soil conditions suitable for subsequent crops (McPhee et al., 2015).

Soil compaction has negative impacts on many soil organisms (Beylich et al., 2010; Brussaard and van Faassen, 1994; Pangnakorn et al., 2003; Whalley et al., 1995), partly as a consequence of the reduced volume and connectivity of soil pores. Many soil organisms (e.g. mites and Collembola, which often number in the tens of thousands per square meter) have no capacity to burrow or dig through the soil, and rely on interconnected soil pores for their physical habitat (Gupta, 1994; Lee and Foster, 1991). Soil compaction represents a loss of habitat for these organisms. For the few soil invertebrates, such as earthworms, ants, beetles and some insect larvae, that are capable of

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Nomenclature

Berlese-Tullgren funnel — an apparatus consisting of a funnel with a gauze insert, overhead light for warmth, and a capture bottle containing ethanol below the funnel. It is used to extract living organisms, particularly arthropods, from samples of soil and is normally arranged in a bank of multiple units
CTF — Controlled Traffic Farming
GNSS — Global Navigation Satellite Systems
Track gauge — the centre to centre distance between tyres across a machine, perpendicular to the direction of travel

actively burrowing, compacted soils may be habitable, but are a less desirable habitat than uncompacted soils (Beylich et al., 2010).

Many modifications to agricultural management practices have been demonstrated as strategies for reducing soil compaction. These include modifications to implements so that multiple operations (e.g. tillage, sowing, application of fertilisers and pre-emergent herbicides) can be achieved in a single pass, thereby reducing the number of passes required. Minimum tillage, no-till farming and low ground pressure tyres may also reduce the extent of compaction. The most effective strategy for managing compaction in cropping soils is controlled traffic farming (CTF) (Chamen et al., 2003; Chamen, 2015; McPhee et al., 2015; Tullberg, 2010; Vermeulen et al., 2010). CTF relies on all machines having the same track gauge and compatible working widths, and then constraining their movement in the field to permanently defined and located wheel-tracks (Baker et al., 2007). This results in a large area of the field having no traffic, and hence no soil compaction, while a much smaller area becomes permanent wheel-tracks, which may or may not grow crop, depending on the circumstances. Achieving the degree of precision required to maintain this pattern of machinery movement has been greatly aided by the development of GNSS guidance and auto-steering technologies, although dimensionally incompatible machinery designs are a major hurdle to adoption in some industries (McPhee and Aird, 2013).

When assessing the status of soil biology, it is generally impractical to collect data for all organisms present. The soil biota is comprised of such a wide range of different taxonomic groups that such a comprehensive study would require a diverse range of expertise and research methodologies. This problem is overcome by selecting a subset of ‘indicator taxa’ for study on the assumption that they will provide some insight into the status of the remaining biota (King and Hutchinson, 2007; Pankhurst et al., 1995; Paoletti et al., 2007a,b). In this study, soil arthropods identified to the level of Order, and the Collembola, identified to species level, were used as indicators. Soil arthropods include groups such as the collembolan and oribatid mites, which are primarily grazers of the microorganisms found in decomposing organic materials, and predators such as micro-spiders, centipedes and mesostigmatid mites, which prey upon a range of organisms including nematodes, protozoa and other arthropods. The merits of arthropods as indicators of biological properties in agricultural soils are discussed extensively by King and Hutchinson (2007); Pankhurst et al. (1995); Paoletti et al. (2007a,b), and the usefulness of Collembola as indicators by Greenslade (2007).

In this study, the effects of a controlled traffic management system on soil biological properties were assessed. The benefits of controlled traffic farming for reducing soil compaction and improving soil structure have been widely reported over many years (Bakker and Barker, 1998; Chamen and Longstaff, 1995; Gerik et al., 1987; McHugh et al., 2009; McPhee et al., 2015; Tisdall and Adem, 1988). This study was undertaken to determine if changes in traffic and tillage management under controlled traffic led to responses in soil arthropod abundance and richness. The null hypothesis was that there would be no impact on the relative composition and abundance of soil arthropods, when measured by depth and season, as the result of controlled traffic management.

2. Materials and methods

2.1. Site description

The experimental site was located in a 1.6 ha field on the Tasmanian Institute of Agriculture Vegetable Research Facility, approximately 9 km west-south-west of Devonport, Tasmania, Australia (41°12′20″ S, 146°15′50″ E). The site has deep, friable, Red Ferrosol soils (Isbell, 2002), representative of prime vegetable production areas in Tasmania. Characteristics of the soil at the site are described in McPhee et al. (2015). The farm has an elevation of 90–150 m and an undulating topography ranging from 2–16% slope. The site used in this study had an average slope of 6%, ranging from 2.5–9%. Rainfall is winter dominant, with a long term average of 980 mm/y. Irrigated summer cropping is the main enterprise of the region, although rain-fed winter crops are also grown.

2.2. Experimental design

The experiment site was established as two replications of two treatments – controlled traffic (CT), with all wheel traffic confined to permanent wheel tracks on a track gauge of 2 m, and conventional practices using random traffic (RT). Each treatment plot was transected by three equally spaced sampling areas, as described in McPhee et al. (2015). All soil fauna samples were taken from within these sampling areas. This approach was taken to allow for spatial variation, given that the degree of replication was limited by field layout and the logistics of machinery operation, particularly at harvest.

2.3. Site management during the study period

Details of site establishment and management are outlined in McPhee et al. (2015). A number of vegetable and cover crops was grown on the site during the study. Twice the number of tillage operations were used on the RT treatment over the full course of the work. This difference in tillage management was a direct consequence of the isolation of machinery traffic from the cropping bed in the CT treatments.

2.4. Soil arthropod sampling

Soil cores for arthropod extraction were collected during the growth of the broccoli (*Brassica oleracea* var. *italic*) and carrot (*Daucus carota* subsp. *sativus*) crops (winter and late spring, respectively), 17 months apart. The cores were 160 mm diameter and 50 mm deep, and were taken from 0–50 mm, 70–120 mm and 140–190 mm depths. In both winter and spring, one sampling point was selected within each of the sampling areas in each of the treatment plots (i.e. six sample points within each of the RT and CT treatments). Samples were taken near the centre-line of beds to avoid any influence of the wheel tracks at the bed margins. Soil samples were kept cool during the field sampling process, and transferred to the laboratory within a few hours. Arthropods were extracted from the soil using Berlese-Tullgren funnels over a period of 48 h. The resulting soil layer in the funnel apparatus was 35–40 mm thick. The funnel apparatus used 50 W lamps, placed approximately 150 mm above the surface of the soil samples, to provide gentle heating and drying. At the completion of extraction, the temperature of the soil sample ranged from 60 °C at the surface, to 45 °C at the base. Extracted organisms were preserved in 95% ethanol. All arthropods were identified to the level of order and counted using a stereomicroscope. All Collembola were sorted into morphospecies and counted. Several specimens of each collembolan morphospecies were then slide-mounted in Hoyer's medium and identified as taxonomic species, or as morphospecies within a genus where this was not possible.

Raw counts of arthropod numbers, being the sum of the total number of organisms extracted from the three sampling areas per plot, are provided as supplementary data (Appendix A). The data are categorized by order and species, depth, treatment and season. To allow comparison with other studies, the data concerning abundance may be transformed to numbers of individuals per m^2 (multiply by 16.58) or to numbers of individuals per cm^3 (divide by 3016), given the sampling core dimensions (160 mm dia. ×50 mm height) and that three subsamples were combined to give the total count per plot.

2.5. Data analysis

Data were processed to produce values for six ecological response variables for each sample. These were: abundance of arthropods, ordinal richness (number of arthropod orders), ordinal composition (which orders were present), collembolan abundance (number of Collembola), collembolan species richness (number of collembolan species) and species composition (which collembolan species were present).

The analysis allowed for the experimental structure, being a randomised block design with two replicates, one treatment with two levels (controlled traffic, random traffic), one treatment with three levels (3 depths), season (2 levels), and their interactions. All ANOVA were calculated using Proc Mixed in SAS v9.3 (SAS Institute Inc., Cory, NC, USA). Where appropriate, pairwise comparisons were calculated and Tukey's method used to adjust the p values. F-tests were calculated using Proc PLM to compare the levels of one factor in an interaction for each level of the other. Statistical significance is reported up to $p = 0.10$, since it is known that large scale field experiments in general, and studies of soil organisms in particular, are prone to large variations in measured data (Bedano et al., 2011; Behan-Pelletier, 2003; Osler et al., 2000; Treonis et al., 2010; Vreeken-Buijs et al., 1998). Further, Godwin et al. (2015) argue that zealous adherence to rigorous statistical significance levels can lead to the rejection of valuable trends when comparing the impact of farming systems, and the results of this study indicate beneficial soil impacts due to a farming system change.

Among the Collembola collected, there were several which occurred in a majority of samples across seasons, treatments and sampling depths, thus providing sufficient non-zero data for a compositional analysis (Aitchison, 1986). Some additional criterion was therefore required for selecting a subset of these (i.e. three species) for the analysis. In this case, we selected representative species with distinct ecomorphologies on a gradient from typically epedaphic to euedaphic (i.e. from surface dwelling to true soil dwelling species). These were: *Cryptopygus* sp., a highly pigmented (blue-black) species with well-developed and pigmented ocelli and well developed legs, antennae and furca (epedaphic); *Isotoma* (*Parisotoma*) sp., a lightly pigmented (pale grey) species with lightly pigmented ocelli and well developed legs, antennae and furca (epedaphic/edaphic); and *M. macrochaeta*, a non-pigmented species without ocelli or a furca and with relatively short legs and antennae (euedaphic).

The compositional analysis was performed using multivariate analysis of variance (MANOVA) in the R package 'compositions' (van den Boogaart et al., 2014) to assess the influence of treatment, depth and season on the proportions of the three main orders and the three dominant Collembolan species present. Compositional analysis requires transforming the proportions using an isometric log ratio transform, performing an analysis, and then back-transforming the results such that the components sum to 1.

3. Results

3.1. Arthropod and collembolan assemblages

In winter, 2999 arthropods (1943 from CT and 1056 from RT) were collected from 11 orders, and in spring, 6923 (5150 from CT and 1773 from RT) were collected from 16 orders (Appendix A). Dipteran larvae, Hemiptera, Julid millipedes, Orthoptera and Psocoptera were found only in the spring samples. The oribatid and mesostigmatid mites and Collembola collectively comprised 97% of the fauna in winter, and 94% in spring.

Collembola represented 33% of the fauna in winter and 47% in spring. A total of 18 species of Collembola were found in the aggregate of samples collected, with 16 species being found in winter and 17 in spring. All were identified to genus level and ten as recognised species. One species, *Oncopodura* sp., is the first record for this genus outside cave systems in Tasmania and may represent an as yet undescribed species. Some clear seasonal differences emerged among the collembolan fauna such that 977 individuals were collected in winter while 3129 were collected in spring (Appendix A). This fauna was numerically dominated by two species, although the pattern of dominance changed seasonally. *Mesaphorura macrochaeta* (Rusek, 1976) represented 35% of the Collembola collected in winter, but declined to 12% in spring, whereas *Parisotoma notabilis* represented 16% of the fauna in winter, and increased to 54% in spring.

3.2. Effects on abundance

In spring, arthropod and collembolan abundance was significantly higher at every depth in CT compared to RT (Table 1). Further,

Table 1
Mean counts of arthropods and Collembola in samples collected from Controlled Traffic (CT) and Random Traffic (RT) treatments.

Season	Depth (mm)	Arthropod abundance				Collembolan abundance			
		CT	RT	p	F value	CT	RT	p	F value
Winter	0–50	153	107	0.140	2.5	38	59	0.287	1.3
	70–120	70	38	0.300	1.2	27	13	0.481	0.5
	140–190	101	31	0.036	5.7	19	7	0.518	0.5
Spring	0–50	515	200	< 0.0001	117.2	222	54	< 0.0001	85.7
	70–120	172	50	0.002	16.6	95	30	0.005	12.4
	140–190	171	46	0.001	18.4	100	21	0.001	18.1

S.E. means: Arthropod abundance = 20.6; Collembolan abundance = 13.1; df = 11; n = 6.

arthropod abundance was greater under CT at 140–190 mm in winter, being the only depth to show a difference in winter.

Not only was the spring arthropod and collembolan abundance significantly higher under CT at each depth, but the abundance under CT at 140–190 mm depth was greater than the 70–120 mm abundance under RT ($t_{11} = 4.2$, $p = 0.04$ for arthropod abundance; $t_{11} = 3.8$, $p = 0.07$ for collembolan abundance). There was also no significant difference in the spring abundance for either arthropods generally, or Collembola in particular, between the 0–50 mm depth under RT and the 70–120 mm and 140–190 mm depths under CT ($t_{11} = -0.95$, $p = 1.0$ and $t_{11} = -0.98$, $p = 1.0$ for arthropods at the respective depths, and $t_{11} = 2.2$, $p = 0.6$ and $t_{11} = 2.5$, $p = 0.4$ for Collembola).

3.3. Effects on richness

Table 2 shows differences in arthropod and collembolan richness by treatment, season and depth. For the arthropods, these results mirrored those of abundance, showing that in spring, arthropod richness was significantly higher at every depth in CT compared to RT, and also under CT at 140–190 mm in winter, being the only depth to show a difference in winter.

Unlike the abundance data, there were no significant differences in collembolan richness in spring. The only difference in collembolan richness was noted in winter at 140–190 mm depth when richness was greater under CT than RT ($p = 0.064$).

3.4. Compositional analysis–arthropod orders

The arthropods recovered in the sampling program were predominantly representative of three orders, being Oribatida, Mesostigmata and Collembola. Compositional analysis was undertaken to determine the influence of treatment, depth and season on the proportions of these three orders. The small percentage of arthropods that did not belong to these orders (3% in winter, 6% in spring) were excluded from this analysis. The analysis showed that in winter, the relative proportions of these three orders changed with both treatment ($F_{2,31} = 3.4$, $p = 0.046$) and depth ($F_{4,64} = 3.3$, $p = 0.017$), while in spring, depth was the only influencing factor ($F_{4,66} = 6.7$, $p = 0.0001$). Table 3 shows the mean proportions and the standard deviations of the proportions for all treatments, seasons and depths.

Under RT in winter, the proportion of Oribatida changed very little with depth, ranging from a low of 0.17 at 0–50 mm to a high of 0.23 at 140–190 mm. In contrast, the proportion of Mesostigmata steadily increased (0.16 at 0–50 mm to 0.47 at 140–190 mm) while Collembola steadily decreased (0.67 at 0–50 mm to 0.29 at 140–190 mm). Compared to the RT treatment, the CT winter samples showed less variability in the proportions of orders, and some reversals in trend. Mesostigmata ranged from 0.17 at 0–50 mm to 0.29 at 140–190 mm. Both Oribatida (0.54 at 0–50 mm to 0.38 at 140–190 mm) and Collembola (0.30 at 0–50 mm to 0.23 at 140–190 mm) declined with depth, although the magnitude of the change was not as great as those observed under RT.

The winter results, for which both depth and treatment were significant effects, are shown in ternary diagrams (Fig. 1). Raw data and calculated means for both treatments are shown for each depth, with grid lines represent the changing proportions on each axis.

3.5. Compositional analysis–collembolan species

Summary statistics for the three species chosen for compositional analysis (*Cryptopygus* sp.; *Isotoma* (*Parisotoma*) sp., and *M. macrochaeta*) are presented in Table 4. The MANOVA results showed that for both winter and spring there was a significant effect of both treatment and depth on the proportions of these species without significant interactions of these effects. The imposed treatments were significant in both summer and winter ($F_{2,31} = 3.7$, $p = 0.036$ and $F_{2,31} = 9.3$, $p = 0.0007$, respectively). Although the significance of depth was marginal ($p = 0.09$) in winter, the effect of depth in spring was sig-nificant ($p = 0.0015$). There were also significant seasonal differences in the proportions of these species ($F_{2,65} = 26.1$, $p < 0.0001$) which did not interact significantly with the other effects.

Table 4 shows that one of the major seasonal differences was the dominance of *Isotoma* (*Parisotoma*) at all depths under both treatments in spring, whereas in winter, *M. macrochaeta* was dominant at all depths under CT and at 70–120 mm and 140–190 mm depths under RT. One of the main depth effects was that *Cryptopygus* sp. was a substantial component of the fauna only in the uppermost soil layer, becoming a minor component in the deeper layers. The major treatment effect appears to have occurred in the surface layer of soil in the winter data where *Cryptopygus* sp. and *Isotoma* (*Parisotoma*) sp. were the dominant species under RT, whereas *M. macrochaeta* was dominant under CT.

Beyond the proportion data used in the MANOVA, there were also several noteworthy differences in the collembolan assemblage under the CT and RT treatments. The summary data (Appendix A) shows that in addition to the three species used in the compositional analysis (*Cryptopygus* sp., *Isotoma* (*Parisotoma*) sp. and *M. macrochaeta*), *Onycopodura* sp., *Protaphorura* sp. and *Pseudosinella* sp. were all substantially more abundant under CT than RT, especially in spring.

4. Discussion

Analysis of the data addressed three factors – treatment, depth and season – and their effect on the abundance and richness of soil arthropods generally, and Collembola in particular, and the proportions

Table 2
Mean scores of arthropod and collembolan richness in samples collected from Controlled Traffic (CT) and Random Traffic (RT) treatments.

Season	Depth (mm)	Arthropod richness				Collembolan richness			
		CT	RT	p	F value	CT	RT	p	F value
Winter	0–50	4.2	4.3	0.822	0.1	6.2	7.5	0.197	1.9
	70–120	4.3	4.3	1.000	0.0	6.7	5.0	0.114	2.9
	140–190	5.5	4.2	0.093	3.4	5.5	3.5	0.064	4.2
Spring	0–50	8.5	6.3	0.012	9.0	8.7	7.5	0.255	1.4
	70–120	8.0	5.3	0.004	13.6	5.8	5.5	0.738	0.1
	140–190	7.0	5.7	0.093	3.4	6.3	5.3	0.326	1.1

S.E. means: Arthropod richness = 0.51; Collembolan richness = 0.69. df = 11.

Table 3
Mean proportions (and standard deviations) of Mesostigmata, Oribatida and Collembola in samples collected from Controlled Traffic (CT) and Random Traffic (RT) treatments over two seasons.

Treatment	Season	Depth	Mesostigmata	Oribatida	Collembola
CT	Winter	0–50	0.17 (0.79)	0.54 (1.34)	0.30 (0.74)
		70–120	0.24 (0.26)	0.37 (0.51)	0.39 (0.41)
		140–190	0.39 (0.65)	0.38 (0.87)	0.23 (0.43)
	Spring	0–50	0.14 (0.50)	0.42 (0.56)	0.45 (0.46)
		70–120	0.27 (0.47)	0.09 (0.78)	0.64 (0.40)
		140–190	0.28 (0.81)	0.07 (0.96)	0.65 (0.27)
RT	Winter	0–50	0.16 (0.85)	0.17 (1.06)	0.67 (0.34)
		70–120	0.41 (0.89)	0.19 (0.73)	0.40 (0.36)
		140–190	0.47 (1.11)	0.23 (0.84)	0.29 (0.75)
	Spring	0–50	0.11 (0.43)	0.54 (0.66)	0.35 (0.39)
		70–120	0.25 (0.37)	0.10 (0.92)	0.65 (0.74)
		140–190	0.41 (0.17)	0.14 (0.81)	0.45 (0.85)

of the three dominant orders of arthropods, and species of Collembola.

Each of these variables can be expected to respond with varying sensitivity to environmental variation. For example, in very similar environments, a minor difference in availability of resources could be expected to cause a difference in the overall abundance of arthropods but not in which orders were present. Conversely, a difference in ordinal composition (such as the absence of spiders in one block of samples while they were present in another) would be interpreted as indicating more significant environmental variation. At the most sensitive end of this spectrum, since the environmental requirements of any given species can be assumed to be more constrained than the requirements of all species within the same order; the species composition within a sample can be taken as a more sensitive variable than the raw abundance of all species within that order.

4.1. The influence of controlled traffic

The results of this study show that overall, arthropod and collembolan abundance were significantly higher under a controlled traffic system of management compared to the random traffic system, with highly significant differences in the spring samples. These differences extended to differences in the diversity of the arthropod assemblage under controlled traffic, also in the spring samples. The only differences evident in winter samples were at the lowest depth of sampling.

It has been reported previously that controlled traffic can reduce both soil compaction and the number of tillage operations required to produce a seed bed in vegetable production systems (McPhee et al., 2015). There are two major differences in relation to soil management between controlled traffic and random traffic systems. Firstly, under controlled traffic, soil compaction due to machinery traffic is isolated to permanent wheel tracks. Consequently, there is a reduced need for tillage compared to the random traffic system, with a 50% reduction in the number of tillage operations over the full crop sequence of this study. Tillage and traffic are closely linked, in that the reason for many

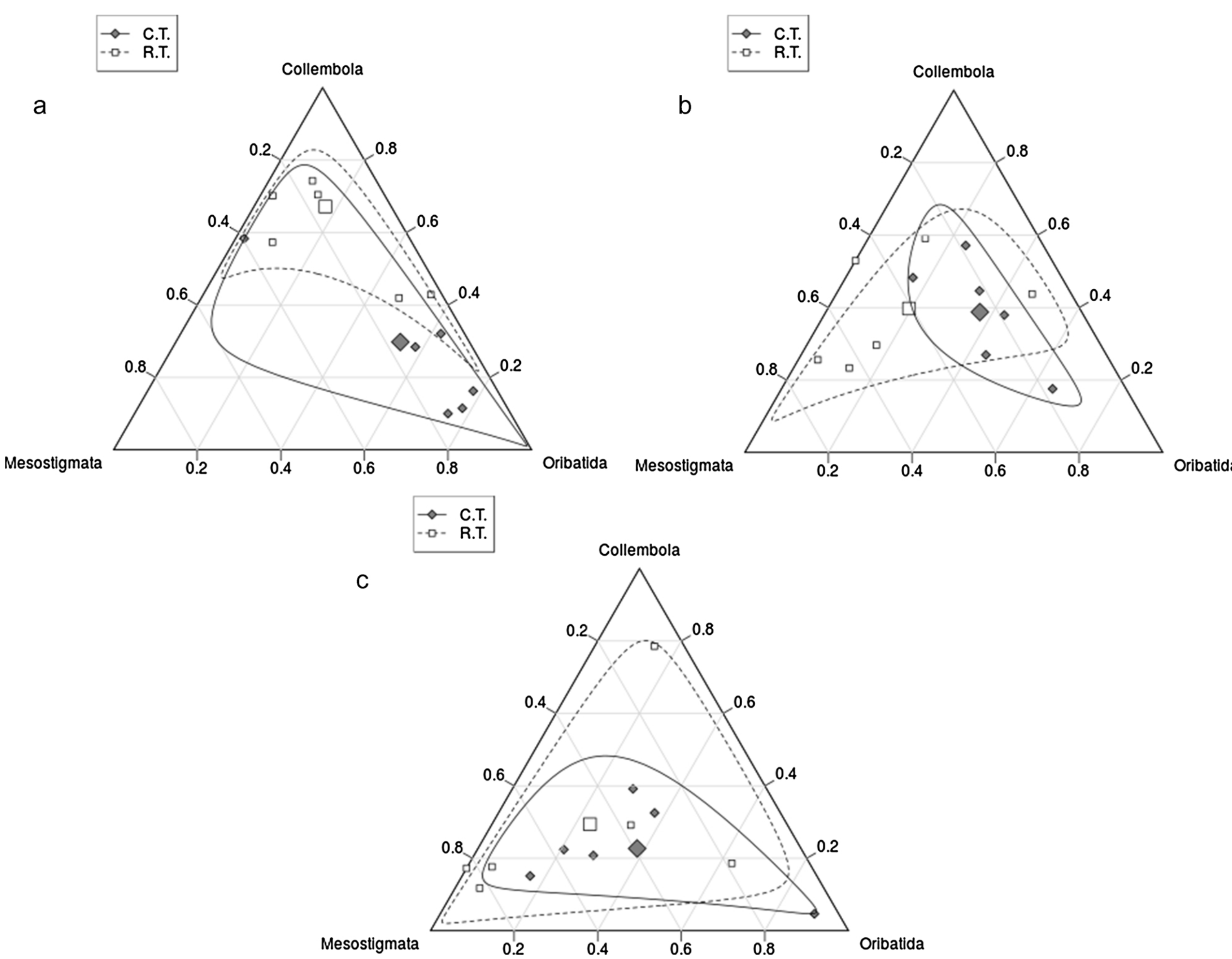

Fig. 1. Mean proportions of Mesostigmata, Oribatida and Collembola under RT and CT in winter: (a) 0–50 mm depth, (b) 70–120 mm depth, (c) 140–190 mm depth. Small symbols represent observed data, large symbols represent the mean proportion. The boundaries indicate approximate 95% confidence limits.

Table 4
Mean proportions (and standard deviations) of *Cryptopygus* sp., *Isotoma* (*Parisotoma*) sp. and *Mesaphorura macrochaeta* in samples collected from Controlled Traffic (CT) and Random Traffic (RT) treatments over two seasons.

Treatment	Season	Depth	*Cryptopygus* sp.	*I.* (*Parisotoma*) sp.	*M. macrochaeta*
CT	Winter	0–50	0.021 (1.955)	0.003 (1.906)	0.976 (1.152)
		70–120	0.007 (1.825)	0.004 (1.904)	0.989 (1.166)
		140–190	0.001 (1.051)	0.019 (1.878)	0.980 (0.995)
	Spring	0–50	0.065 (1.925)	0.782 (1.011)	0.153 (1.444)
		70–120	0.001 (1.614)	0.833 (0.895)	0.166 (0.864)
		140–190	0.001 (1.608)	0.917 (1.214)	0.082 (0.805)
RT	Winter	0–50	0.109 (2.157)	0.808 (0.974)	0.083 (2.387)
		70–120	0.054 (1.654)	0.203 (2.686)	0.743 (2.118)
		140–190	0.026 (1.001)	0.121 (2.083)	0.852 (2.241)
	Spring	0–50	0.403 (1.016)	0.569 (1.341)	0.029 (1.965)
		70–120	0.004 (1.951)	0.977 (1.673)	0.018 (2.524)
		140–190	0.011 (2.555)	0.797 (0.729)	0.192 (2.478)

tillage operations is to remediate soil compaction. Despite the linkage between these factors, there are important ecological distinctions between their effects. Tillage functions as an intermittent disturbance from which soil arthropod populations adapted to disturbance will recover, depending upon its frequency and intensity. However, soil compaction imposes qualitative and quantitative changes on the resources available to soil arthropods (e.g. the volume and structure of soil pore spaces, relative proportions of water, soil and air within the soil profile, frequency of water-logging etc.), which may represent semi-permanent constraints on soil arthropod populations if some form of remedial management does not occur.

Reviews of the literature concerning impacts of tillage on soil biological properties suggest varying responses, especially with regard to the Collembola (Capelle et al., 2012; Cluzeau et al., 2012; Kladivko, 2001; Wardle, 1995). Reducing tillage may increase, decrease or make no difference to the abundance and diversity of soil arthropods (Brennan et al., 2006; Dubie et al., 2011; Stinner and House, 1990; Petersen, 2002; Sabatini et al., 1997; Wardle, 1995). These differences in response are not well explained.

With few exceptions (Dittmer and Schrader, 2000; Schrader and Lingnau, 1997; Winter et al., 1990), studies and reviews of the effects of management on soil biota tend to focus on either tillage (Alvarez et al., 2001; Brennan et al., 2006; Dubie et al., 2011; Longstaff et al., 1999; Neave and Fox, 1998) or traffic compaction (Beylich et al., 2010; Heisler and Kaiser, 1995; Larsen et al., 2004; Whalley et al., 1995). Very few studies report on the combined influence of changes in traffic and tillage management as seen under controlled traffic (Pangnakorn et al., 2003; Stirling, 2008).

Another important consideration in interpreting collembolan abundance as a response to soil compaction and tillage is the occurrence of species specific responses. Sabatini et al. (1997) found that *P. notabilis, Onychiurus armatus* and *Neotullbergia ramicuspis* were more abundant under minimum tillage while *Onychiurus insubrarius* and *E. multifasicata* were more abundant in conventionally ploughed fields. Similar effects have also been reported by Dittmer and Schrader (2000) and Brennan et al. (2006). Differential effects of soil compaction on collembolan species have also been demonstrated by Larsen et al. (2004) who found that the abundance of *M. macrochaeta* and *Protaphorura armata* declined in compacted soils, but the abundance of *Folsomia fimetaria* did not. Whether it is a consequence of tillage or compaction, changes in the abundance of Collembola should be evaluated with caution, since they may mask such differential effects. The literature provides little guidance concerning the combined effects of tillage and compaction on soil arthropods, since it often fails to disentangle the effects of these two factors and frequently does not deal with species specific effects.

Although there was a 50% reduction in the number of tillage operations under CT compared to RT over the course of this study, it is acknowledged that the tillage operations undertaken were still very much of a conventional nature (e.g. rip, rotary hoe etc.), and hence would have been highly disruptive to the soil environment from the perspective of arthropod habitat. This suggests that the absence of machinery induced soil compaction was a major influence on the provision of a soil environment which was more hospitable to soil arthropods, particularly under spring conditions.

Interpretation of the results from the winter data set is somewhat problematic. The results show seasonally lower arthropod abundance and arthropod and collembolan richness at all depths except 140–190 mm, which would have been below the depth of powered tillage operations. This, at least potentially, reduces the detectability of ecological responses. In samples that were taken in the same week as the winter arthropod samples, McPhee et al. (2015) reported significantly lower bulk density, and higher total and air-filled porosity at a sampling depth of 150 mm, and this may help explain the differences observed at depth. Further, the only tillage operation conducted under CT in the period leading up to the winter arthropod sampling was a bed-edge rip and roll. This was performed with a deep ripper with only two tines, one at each edge of the bed, to remediate encroachment of wheel traffic compaction due to the prior onion harvest operation. The rolling was done to provide a smooth surface for operation of the broccoli transplanter. As a result, the soil in the centre of the CT beds at the time of winter sampling had not been disturbed by tillage for almost 12 months, but had been surface rolled. This combination of actions may go some way to explaining why the soil environment under CT at 140–190 mm depth favoured an increased abundance and species diversity, while the results at shallower depths were not significantly different.

Further indications of a positive effect of CT are found in a broader consideration of the whole ordinal and species assemblage (Appendix A). For example, outside of the three dominant orders used in the analysis (Mesostigmata, Oribatida and Collembola), the number of individuals from other orders recovered from CT samples was higher than those collected from RT samples by a factor of 1.6 in winter and 3.2 in spring, even though the ordinal richness was very similar for both treatments. Even though these organisms were only a minor numerical component of the whole arthropod assemblage (approx. 3% in winter and < 7% in spring), they contributed to the overall population of the assemblage, particularly under CT. Within the collembolan assemblage, outside of the three dominant species used in the analysis (*Cryptopygus* sp., *Isotoma* (*Parisotoma*) sp. and *M. macrochaeta*), the number of individuals of other species recovered from CT samples was higher than those collected from RT samples by a factor of 1.2 in winter and 1.8 in spring, even though the species richness was very similar for both treatments. In this case, these organisms represent up to 40% of the total number of individuals in the Collembolan assemblage.

4.2. Interactions with depth

A rapid decline in abundance with depth was observed for both arthropods and Collembola (Table 1). This is in accordance with the usual distribution of these organisms, which are generally found in the surface layers of the soil (Gupta, 1994; Lee and Foster, 1991).

While this decline is to be expected, the abundance of arthropods at the two lower depths under CT was not significantly different from the 0–50 mm abundance for RT, particularly in spring. This indicates that the benefits of CT extend to depth, such that population numbers found only in the surface layer under RT were found at depth under CT. This suggests CT provides a soil environment that is more hospitable to arthropods.

To a substantial extent, the results for ordinal composition (Table 3) may be explained by the generalized differences in body size of these orders. The Collembola, for example, generally range from 0.2–6.0 mm in length, whereas oribatid mites range from 0.2–1.5 mm in length. Many of the mesostigmatid mites recovered from the samples were nymphal stages, which were generally less than 1 mm in length. As the largest of these three orders, the Collembola, might be expected to be more constrained by decreasing soil pore space with increasing depth, compared to the oribatid or mesostigmatid mites. Indeed, if CT helps maintain pore space with depth, it is to be expected that the decline of Collembola with depth would be less pronounced, as is shown in these results.

The results for *Cryptopygus* sp. are especially interesting, as they suggest that for epedaphic species, which are adapted to a life on the soil surface, no amount of soil compaction alleviation will lead to larger populations in the deeper soil (they simply don't like it down there). It may therefore be beneficial to focus future studies on species which would benefit from modifications to the soil environment at depth i.e. euedaphic species such as *M. macrochaeta*, *Oncopodura* sp., *Protaphorura* sp. etc.

4.3. Interactions with season

The influence of season on arthropod and collembolan abundance was quite marked (Table 1). It is not uncommon to have such stark seasonal differences, as it is known that soil biological communities fluctuate with the seasons (Osler et al., 2000), with higher abundances occurring in spring and autumn (Anderson, 1988). The significantly higher abundance recorded under CT, compared to RT, once again indicates that CT has beneficial effects on the soil environment in terms of arthropod habitat, particularly in spring.

Arthropod ordinal richness was highest under CT in the spring, and at this time, was significantly greater than all other season x treatment combinations, although a similar effect was not observed for collembolan richness. Although a seasonal difference in the number of arthropod orders collected in any set of samples comparing winter and spring is unremarkable, the treatment effect is not. Under CT in spring there were consistently more arthropods collected per sample (Appendix A). Interestingly, this is not a function of there being more orders present under CT, since 14 orders were collected under both CT and RT in spring. This pattern emerges because of consistently higher total counts in CT compared to RT for almost all orders, and usually by a considerable margin (Appendix A).

The compositional analysis of the collembolan species data showed significant seasonal effects. It is clear that, at least in temperate regions, the overall abundance of Collembola increases substantially in the warmer months, which may provide a stronger and clearer signal of any treatment effects. The species which are numerically dominant also changes on a seasonal basis, so comparisons between different studies must take this into account. Such comparisons should be made with caution in areas where seasonal variations in assemblage structure are unknown.

5. Conclusion

Controlled traffic has many benefits for crop production, ranging from improvements in soil (structure, infiltration, water holding capacity) to improvements in timeliness, yield and overall system productivity (Batey, 2009; Chamen, 2015; Chen et al., 2008; McHugh et al., 2009; McPhee et al., 2015, 1995; Spoor, 1997; Tullberg, 2010). The results of this study further demonstrate that controlled traffic offers benefits for the sustainability of soil biology in cropping systems, with particular reference to soil arthropods. Despite difficulties in the attribution of arthropod responses to specific factors (i.e. compaction or tillage), in every case where significant effects occurred, they represent positive responses of the arthropod assemblage to the controlled traffic treatment. Therefore, it can be reasonably concluded that the controlled traffic management system, which isolates soil compaction away from the growing bed, and reduces frequency and intensity of tillage operations, has beneficial effects on the abundance and diversity of soil arthropods.

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Appendix A

Table A1

Summary statistics of arthropod and collembolan assemblages

	Winter											
Treatment	**Controlled traffic**					**Random traffic**					**Grand total**	
Sampling depth (mm)	**0-50**	**70-120**	**140-190**	**Total collected**	**% of fauna**	**0-50**	**70-120**	**140-190**	**Total collected**	**% of fauna**	**Total collected**	**% of fauna**
Arthropod Orders												
Aranea	1		1	2	0				0	0	2	0
Coleoptera		1		1	0	3	2	1	6	1	7	0
Collembola	230	160	115	505	26	354	79	41	474	45	979	33
Diplura		1	15	16	1				0	0	16	1
Diptera				0	0				0	0	0	0
Hemiptera				0	0				0	0	0	0
Julida				0	0				0	0	0	0
Lepidoptera				0	0	2	1		3	0	3	0
Lithobiida	2			2	0	3			3	0	5	0
Mesostigmata	121	97	197	415	21	95	103	96	294	28	709	24
Oribatida	556	149	261	966	50	179	33	41	253	24	1219	41
Orthoptera				0	0				0	0	0	0
Pauropoda	1	4	4	9	0	1	5	4	10	1	19	1
Protura	2	1	4	7	0		1		1	0	8	0
Psocoptera				0	0				0	0	0	0
Symphyla	5	6	9	20	1	3	5	4	12	1	32	1
Total Invertebrates	**918**	**419**	**606**	**1943**	**100**	**640**	**229**	**187**	**1056**		**2999**	
Invertebrate Richness	**8**	**8**	**8**	**10**		**8**	**8**	**6**	**9**		**11**	
Collembola species												
Arrhopalites sp	10	5	1	16	3	4	4		8	2	24	2
Bourletiella hortensis	14	1	2	17	3	12	5	1	18	4	35	4
Ceratophysella denticulata				0	0	3	1		4	1	4	0
Cryptopygus sp	8	3		11	2	67	3		70	15	81	8
Entomobrya multifasicata		3	1	4	1	2		2	4	1	8	1
Entomobrya unostrigata				0	0	1	1		2	0	2	0
Heteromurus sp.	1			1	0				0	0	1	0
Hypogastrura manubrialis	23	8	10	41	8	21	15	9	45	10	86	9
Isotoma (Parisotoma) sp	2	4	7	13	3	133	10	2	145	31	158	16
Isotomidae Gen. Sp. FH	6	4	7	17	3	31	5	7	43	9	60	6
Isotomiella prussianiae				0	0				0	0	0	0
Isotomurus sp.		1		1	0	1	1		2	0	3	0
Megalothorax sp	24	15	12	51	10	13	3	7	23	5	74	8
Mesaphorura macrochaeta	115	100	51	266	53	37	27	10	74	16	340	35
Oncopodura sp	6	8	11	25	5				0	0	25	3
Protaphorura				0	0				0	0	0	0
Pseodosinella sp	1	5	8	14	3	1			1	0	15	2
Sphaeridia sp.	19	3	5	27	5	27	4	3	34	7	61	6
Total Collembola	**229**	**160**	**115**	**504**	**100**	**353**	**79**	**41**	**473**		**977**	
Collembolan richness	**12**	**13**	**11**	**14**		**14**	**12**	**8**	**14**		**16**	

(continued on next page)

Table A1 (*continued*)

	Spring											
Treatment	**Controlled traffic**					**Random traffic**					**Grand total**	
Sampling depth (mm)	**0-50**	**70-120**	**140-190**	**Total collected**	**% of fauna**	**0-50**	**70-120**	**140-190**	**Total collected**	**% of fauna**	**Total collected**	**% of fauna**
Arthropod Orders												
Aranea			1	1	0				0	0	1	0
Coleoptera	15	3	3	21	0	5	3	3	11	1	32	0
Collembola	1427	586	600	2613	51	328	185	133	646	36	3259	47
Diplura	16	15	9	40	1			1	1	0	41	1
Diptera	3	19	15	37	1	6	9	6	21	1	58	1
Hemiptera	12			12	0	12			12	1	24	0
Julida	29	15	17	61	1	1	9		10	1	71	1
Lepidoptera		12	9	21	0	6	2	4	12	1	33	0
Lithobiida	9	3	1	13	0	2	2	1	5	0	18	0
Mesostigmata	367	248	263	878	17	94	64	97	255	14	1133	16
Oribatida	1183	84	54	1321	26	733	16	16	765	43	2086	30
Orthoptera				0	0	1			1	0	1	0
Pauropoda	4		4	8	0	1		5	6	0	14	0
Protura	4	5	10	19	0				0	0	19	0
Psocoptera				0	0	1			1	0	1	0
Symphyla	22	42	41	105	2	8	8	11	27	2	132	2
Total Invertebrates	**3091**	**1032**	**1027**	**5150**		**1198**	**298**	**277**	**1773**		**6923**	
Invertebrate Richness	**12**	**11**	**13**	**14**		**13**	**9**	**10**	**14**		**16**	
Collembola species												
Arrhopalites sp		1	1	2	0	4	2	4	10	2	12	0
Bourletiella hortensis	4			4	0	8	1	3	12	2	16	1
Ceratophysella denticulata	2	1		3	0	3			3	0	6	0
Cryptopygus sp	215	5	3	223	9	73	3	5	81	13	304	10
Entomobrya multifasicata	1			1	0	2	1		3	0	4	0
Entomobrya unostrigata				0	0	2			2	0	2	0
Heteromurus sp.	1			1	0			1	1	0	2	0
Hypogastrura manubrialis	36	1	2	39	2	23	3	3	29	5	68	2
Isotoma (Parisotoma) sp	676	382	415	1473	59	91	88	40	219	35	1692	54
Isotomidae Gen. Sp. FH				0	0				0	0	0	0
Isotomiella prussianiae	18	10	7	35	1	5	19	23	47	7	82	3
Isotomurus sp.	36		2	38	2	73	16	2	91	14	129	4
Megalothorax sp	8	8	6	22	1	3	6	7	16	3	38	1
Mesaphorura macrochaeta	213	63	41	317	13	28	16	17	61	10	378	12
Oncopodura sp	49	42	40	131	5		4	3	7	1	138	4
Protaphorura	38	39	42	119	5			1	1	0	120	4
Pseodosinella sp	36	17	39	92	4	8	20	17	45	7	137	4
Sphaeridia sp.				0	0	1			1	0	1	0
Total Collembola	**1333**	**569**	**598**	**2500**		**324**	**179**	**126**	**629**		**3129**	
Collembolan richness	**14**	**11**	**11**	**15**		**14**	**12**	**13**	**17**		**17**	

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4.2 Discussion

The origins of controlled traffic centre on the management of soil compaction with the objective of improving crop growth and yield. It is therefore not surprising that soil responses are the most widely reported aspect of controlled traffic research, even within the relatively limited number of articles that relate to controlled traffic in vegetable production. Numerous studies across a range of environments have demonstrated that controlled traffic farming systems result in significant improvements in soil physical conditions and related properties, including reduced bulk density and penetration resistance, increased infiltration and hydraulic conductivity, and increased water content and plant available water (Alvarez & Steinbach, 2009; Bai et al., 2009; McHugh et al., 2009; Tullberg, 2010; Unger, 1996). A large portion of the research reported in the literature comes from zero-till grain production environments. Similar research from vegetable production systems is far less common, with markedly fewer relevant sources available in the literature (Lamers et al., 1986; McPhee et al., 2015; Perdok & Lamers, 1985; Vedie et al., 2008; Vermeulen & Mosquera, 2009).

4.3 Observations in vegetable production

A feature of vegetable production is the regular use of tillage to ameliorate compaction caused by harvest machinery traffic and to manage crop residue to allow operation of vegetable seeding equipment, most of which is unsuited to zero-till operation. Whilst tillage can be used to improve soil structural conditions (e.g. alleviation of soil compaction) the disturbance caused by tillage often has negative consequences for soil function due to a range of factors including changes to soil pore size and continuity and the loss of carbon through oxidation (Douglas & Koppi, 1997; La Scala et al., 2008; McGarry et al., 2000). Given that tillage is still an integral part of vegetable production for crop residue management, it is important to understand if it is possible to improve soil physical conditions purely through traffic management. Data reported in Chapter 4 (McPhee et al., 2015) show that controlled traffic in conjunction with tillage results in improved soil physical properties, as measured by bulk density, porosity and infiltration, compared to random traffic with reliance on tillage to repair compaction damage. In other words, even if tillage is still used to assist seedbed preparation, it is better for the physical condition of the soil to avoid compaction rather than create it and then try to mechanically repair it. Similar conclusions can be deduced from early Dutch work which showed improvements in porosity and aggregate size distribution under controlled traffic management, even though both controlled and random traffic systems were subject to tillage (Lamers et al., 1986).

Infiltration data collected as part of the research reported in Chapter 4 (McPhee et al., 2015) was limited to only two occasions, one in winter and one in spring. While there were no differences in infiltration rate in spring, the differences in winter, when the soil was already wet from rainfall, were highly significant. This has important implications for water infiltration and runoff in a winter dominant rainfall environment. The superior infiltration characteristics of soils managed under controlled traffic could potentially result in significant reductions in runoff and erosion, which, alongside soil compaction, is one for the key soil sustainability issues in the Tasmanian vegetable industry (Cotching, et al., 2002).

4.4 Long term maintenance

It was difficult to establish a path of continuous improvement in soil physical conditions under controlled traffic management in the field research the studies reported in Chapter 4 (McPhee et al., 2015). The variability and gradual loss of improved soil conditions over the latter seasons of the research reflect three key issues facing the implementation of controlled traffic in vegetable production:

1. Dimensional incompatibility of machinery, as outlined in Chapter 3 (McPhee & Aird, 2013). In the case of the work reported for Site 1 in Chapter 4 (McPhee et al., 2015), the crop rotation was chosen to facilitate maintenance of a controlled traffic system for as long as possible, although some machinery options were still sub-optimal for the system.

2. Limited access to tillage machinery specifically designed for use in controlled traffic systems. Some machinery was modified to suit the system, although achieving full compatibility is often an evolutionary process that takes a number of seasons to achieve.

3. Inexperience with management practices suited to non-compacted soils, with consequences such as difficulty in maintaining guidance tracking on compacted wheel tracks (McPhee & Aird, 2013). As noted in the previous point, refining

operations, equipment and management practices often takes several seasons and exposure to differing crops and conditions.

4.5 Alternative measures

There is considerable scope for more research to improve understanding of the impacts of controlled traffic on soil physical properties. The data reported in Chapter 4 (McPhee et al., 2015) relates primarily to measures of soil penetration resistance, and bulk density and soil water content, allowing derivation of measures such as total and air-filled porosity. More intensive studies could add considerably more information on topics such as pore size characterisation, pore connectivity and tortuosity, water holding capacity and water use efficiency, nutrient use efficiency, infiltration and hydraulic conductivity, and erosion and runoff. All of these measures have been shown to improve under controlled traffic management in other industries, such as rain-fed grain production (Bai et al., 2009; Bakker & Barker, 1998; Blanco-Canqui et al., 2010; Boulal et al., 2011; Boulal et al., 2011; Wang et al., 2009), but very little work has been done in vegetable production environments that rely on tillage. None of these factors exist in isolation from each other in the context of soil physical properties, nor from their capacity to influence crop growth. Further, there are intrinsic linkages between soil physical properties and soil biology.

4.6 Soil biology

Studies of soil biology can infer much about the physical status of a soil without necessarily requiring extensive measures of some soil physical properties. The prevalence, diversity and spatial distribution of certain species can be used as an indicator of habitat suitability and hence, by inference, the structure of the soil. This was the approach used in the second paper in Chapter 4 (Rodgers et al., 2018), whereby soil arthropods were used as an indicator of beneficial soil physical structure.

Soil arthropods are unable to burrow and move soil. Therefore, they are dependent on the existing soil physical environment for their habitat. Their number and diversity reflect the suitability of the soil environment in terms of food sources and living conditions, such as aeration and soil moisture content (Chikoski et al., 2006; Dudas et al., 2016; Shakir & Ahmed, 2015). Their spatial distribution, particularly vertically within the soil profile, reflects factors such as pore connectivity since, given their inability to burrow, they can only move deeper into the soil if pore continuity allows them to do so – and provided other environmental factors are suitable.

The data reported in Chapter 4 (Rodgers et al., 2018) shows significant benefits in the controlled traffic soil environment from the perspective of soil arthropods, and in consideration of the points outlined above, this implies improved soil physical conditions. This conclusion obviously concurs with the soil physical data also reported in Chapter 4 (McPhee et al., 2015) and provides an added dimension to the understanding of the connection between soil structure and soil biology under controlled traffic management.

The paper of Rodgers et al. (2018) provides further support to the contention previously presented that avoiding compaction at the outset is a more effective strategy for soil improvement than creating compaction and using tillage for remediation. Both treatments used in the research at Site 1 used tillage as part of seedbed preparation, and so all soil sampled for arthropod collection would have been subject to disturbance that would lead to the destruction of pore continuity. Despite this disturbance, there were still clear advantages for soil arthropod habitat arising from the isolation of soil compaction under controlled traffic. Similar conclusions were reached in a different soil and cropping environment using earthworms as the indicator species (Pangnakorn et al., 2003).

The literature covering soil biological responses to controlled traffic management is particularly sparse, with the Chapter 4 paper (Rodgers et al., 2018) representing one of only three recorded in literature databases. Consequently, as with soil physical properties, there is ample scope for more research into the soil biological aspects of controlled traffic, particularly more longitudinal studies that take into account the impacts of season and the variations within the cropping cycle. There is also a need to link the impact of CTF on soil biology to soil processes and function, particularly in relation to hydrologic and nutrient cycling aspects. As can be seen from identification of these areas of potential investigation, the biological impacts of managing soil compaction through the use of controlled traffic, and the consequent effects that may have on many soil processes, have barely been touched.

4.7 Benefits of soil improvement

Improvements in soil physical and biological conditions are a laudable goal for sustainable agriculture but are generally not sufficient reason to attract interest in the adoption of controlled traffic at the commercial farm level. However, as in all systems, changes in one part of the system influence other parts, and so it is with the changes to soil conditions under controlled traffic.

4.7.1 Yield

The prospect of improved yield is always of interest to growers. As noted in the literature review (Chapter 2), there is considerable evidence to support modest improvements in crop yield through the adoption of controlled traffic. This was not strongly supported in the field research reported in Chapter 4 (McPhee et al., 2015). Only one crop (onions) showed a statistically significant yield increase under controlled traffic. There are likely several factors influencing the capacity to achieve yield increases through the use of controlled traffic in vegetable production:

- Time – while some changes to soil physical conditions can occur quite rapidly with the isolation of soil compaction, it is not unusual for crop responses to take some time to eventuate.

- Accuracy and repeatability – the capacity to maintain compaction-free conditions under controlled traffic depends on access to compatible equipment and the capacity to accurately manage traffic and tillage operations. These issues are significant in the vegetable industry, as noted in Chapter 3 (McPhee & Aird, 2013), and were suboptimal at times during the conduct of the field research reported in Chapter 4 (McPhee et al., 2015).

- Experience – current cropping systems, which are dependent on a range of tillage operations and tools, have developed over many decades of mechanised agriculture. In fact, some tools and management practices have barely changed since the days of the horse, the only significant difference now being the scale and speed of tillage operations permitted by high-powered tractors. The soil conditions prevalent under controlled traffic present a new environment for crop managers. As an industry, agriculture has been dealing with increasingly compacted soils as machinery has increased in size and weight over several decades, the dominant response being to increase the depth and intensity of tillage. Controlled traffic changes the dynamic of the machine-soil interaction. As noted by Chamen (2015) ‘If we can’t get non-trafficked soil to improve in structure and to yield more, we just haven’t learnt how’. It is unlikely that it will take decades to properly understand how to maximise the benefits of non-compacted soil, but it does take time, so we should not be surprised if yields do not significantly increase in the short term.

4.7.2 Timeliness

It is arguable that yield improvement on an individual crop basis may be one of the least important benefits of improved soil conditions under controlled traffic. There are clearly many potential production and environmental benefits related to improved aeration, water infiltration and storage, and water and nutrient use efficiency. One of the key productivity-related benefits arising from controlled traffic is improvements in operational timeliness. This usually comes about due to two key factors – better trafficability on compacted wheel tracks and reduced tillage requirements. The latter point is particularly relevant in vegetable production which still relies heavily on tillage operations for seedbed preparation.

Reductions in tillage requirements influence timeliness in two ways:

- fewer operations to perform, as there is no longer a need to remediate soil compaction

- faster work rates due to lower draft requirements, with implements operating in lower bulk density soils, and potentially at shallower depths (Godwin, 2007; Lamers et al., 1986), which can be reflected in either faster travel speeds with the same equipment, or the same travel speed with wider equipment.

Records from the three field sites reported in Chapter 4 (McPhee et al., 2015) note reductions in the number of tillage operations ranging from 20-57%. In one case, reductions in the number of tillage operations under controlled traffic gave a potential timeliness advantage of four weeks for sowing date, although this did not provide any production advantage as sowing time was dictated by contractual arrangements. It is expected that the number of tillage operations could be further reduced with more experience, with more appropriately designed equipment and with better control over tracking accuracy. Local experience in the Tasmanian vegetable industry since the time of this research reflects these trends. Dedicated equipment choices and changes to operations have led to two-fold increases in operating speeds, a 30% reduction in number of tillage passes and a 50% reduction in tractor size in a fresh vegetable production system based on permanent beds (Kable, 2019). Reductions in tillage operations, and particularly reductions in tractor size (and hence capital cost) are important components of the improved economic performance of controlled traffic farming systems, as outlined in Chapter 5 (McPhee et al., 2016).

4.8 The future

It is clear that controlled traffic management results in improved soil physical and biological conditions, leading to improved soil function and a reduced need for tillage. While zero-till technology is well advanced and adopted in the grain industry, such approaches are in their infancy in the vegetable industry and may well be unachievable for some small-seeded crops, such as carrots. Other approaches to tillage reduction, such as strip-till, may be more appropriate. Strip-till provides the opportunity to significantly reduce both the surface area and volume of soil disturbed in creating seedbed conditions for row crops, generally reducing surface area disturbance to less than 50%. While commercial strip-till technology capable of operating in compacted and untilled soils is now available, during the field research that formed the basis of Chapter 4 (McPhee et al., 2015), a very simple strip-till machine was built specifically with controlled traffic managed soils in mind. This was used at Sites 1 and 3, as reported in Chapter 4 (McPhee et al., 2015). It was estimated that the volume of soil disturbed with this strip-till machine was 90% lower than that resulting from conventional full tillage (J. McPhee, unpub. data). For appropriate crops (i.e. generally those sown on inter-row spacings >200 mm), strip-till provides an ideal approach to managing residue prior to vegetable sowing without the need to resort to complete disturbance tillage, and as such is well suited to incorporation into controlled traffic management.

4.9 Summary

The isolation of traffic compaction away from crop production zones is the fundamental basis of controlled traffic. Soil compaction management was the original driver for controlled traffic. While this has enabled the evolution of many advanced zero-till and crop management practices in the grain industry, it is still very early days in the development of controlled traffic for the vegetable industry. What is clear is that soil management benefits can be achieved in the vegetable industry through the use of controlled traffic, even if tillage remains part of the operational landscape. The continued use of tillage as part of vegetable industry practices potentially reduces the quantum of benefits compared to the zero-till grain environment, although Chapter 4 (McPhee et al., 2015) shows that both soil physical and biological benefits can be obtained, even in full tillage systems. The reducing need for tillage under controlled traffic, which will only accelerate with improved machinery tracking and the adoption of more suitable tillage technology (such as strip-till and automatic depth control based on soil strength), will further enhance the benefits that can be obtained.

CHAPTER 5. ECONOMIC MODELLING OF CONTROLLED TRAFFIC IN VEGETABLE PRODUCTION

5.1 Background

As outlined in Chapter 3 (McPhee & Aird, 2013), machinery diversity and conversion difficulties remain a significant constraint to the adoption of controlled traffic in mechanised vegetable production. Consequently, it is difficult to demonstrate the benefits of adoption of controlled traffic in a farm-scale commercial vegetable production environment. Research reported in Chapter 4 (McPhee et al., 2015) has demonstrated that soil, timeliness and productivity benefits are achievable if traffic can be controlled, even in a production system that still relies on largely conventional tillage practices.

Economic viability is a key consideration in the adoption of new technologies or farming systems. In the absence of commercial operations that can be used as case studies, and with new mechanisation technologies in development, modelling is one of the few options available to provide insight into the potential economic viability of controlled traffic in mixed vegetable production.

The first paper of this chapter reports on the use of modelling to predict the economic performance of four case study farms using three different traffic management systems: 1. conventional random traffic; 2. seasonal controlled traffic, and; 3. fully integrated tractor-based controlled traffic (even though this option is not physically possible within current mechanisation constraints in the Tasmanian mixed vegetable industry).

One potential solution to the dimensional incompatibility of vegetable harvest machinery is the adoption of wide-span technology. Although proven at the prototype level, wide-span tractors are not yet commercially available. Their promise as a solution to controlled traffic in mixed vegetable production was the catalyst for the modelling reported in the second paper of this chapter. Modelling was done using the wide-span purely as a harvest platform, with all other operations conducted by dimensionally integrated tractors and implements, and also for a system that was totally wide-span based for all operations.

The two papers that comprise Chapter 5 are:

McPhee, JE, Maynard, JR, Aird, PL, Pedersen, HH and Tullberg, JN, (2016) 'Economic modelling of controlled traffic for vegetable production', *Australian Farm Business Management Journal*, **13**, 1-17

McPhee, J and Pedersen, HH, (2017) 'Economic modelling of controlled traffic for vegetable production based on the use of wide span tractors', *Australian Farm Business Management Journal*, **14**, 71-88. ISSN 1449-7875

These two chapters have been removed for copyright reasons

5.2 Discussion

Robust economic studies of controlled traffic adoption are uncommon in any industry, let alone the vegetable industry. Ideally, economic case studies would use information from side by side comparisons of CTF and conventional traffic systems operating under commercial conditions. This is unlikely to happen, as once the necessary equipment changes have been made to adopt controlled traffic, growers are unlikely to revert their system to retain or create a random traffic scenario purely for the purposes of generating some economic data. The other approach would be to have pre- and post-conversion comparisons. To be successful, these depend on robust pre-conversion data, which is often missing, and equivalent quality post-conversion data. With digital data collection becoming more common on most machines and many farms, such case studies may be more feasible in the future.

Notwithstanding the possibility of generating longitudinal data that spans the pre- and post-conversion periods, it must be recognised that many system conversions take a number of years, particularly in the grain industry, as growers tend to stage the conversion process in line with normal machinery replacement schedules. This is unlikely to happen in industries like vegetables, in which changes to such basic elements as track gauge may dictate rapid conversion of all machinery used in order to maintain a workable system.

A number of peer-reviewed and grey literature (not refereed) sources were reviewed for the papers that comprise Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017), and while none of them refer to vegetable production systems, the information was used to inform modelling approaches and assumptions. Some economic analyses rely on the upscaling of biophysical research data to commercial enterprise scale (Chamen & Audsley, 1993; Garside et al., 2004). A number of farmer case studies conducted in the cane industry provided useful insights (Carr et al., 2008; East et al., 2012; Halpin et al., 2008; Loeskow et al., 2006; North et al., 2007). Other modelling approaches have been applied to the rain-fed grain industry (Bowman, 2008; Bright & Murray, 1990; Kingwell & Fuchsbichler, 2011).

5.3 Limitations of modelling

As noted in Chapter 3 (McPhee & Aird, 2013), adoption of controlled traffic in vegetable production is challenged by the incompatibility of harvest machinery. Most harvesters are difficult to modify, some are virtually impossible to modify, and finding an acceptable common track gauge and working width combination that suits a diversified industry is nigh impossible. The technology that could potentially overcome this challenge, the wide span (WS) or ‘gantry’ tractor (Chapter 6, (Pedersen et al., 2016)) does not yet exist in a commercial-ready form. Therefore, apart from studying a limited number of examples of controlled traffic adoption in vegetables, such as the very specific situations that occur for Harvest Moon and Mulgowie Farming (Johanson, 2020; Kable, 2019) mentioned in the literature review (Chapter 2) and the Chapter 3 Discussion, modelling is probably the only option currently available to gain some understanding of the potential economic benefits of more ‘universal’ controlled traffic systems in mechanised vegetable production.

Given the previous comments about modification difficulties, economic modelling of tractor-based CTF systems must be based on the notion that harvesters could be modified to suit the system and therefore permit a fully integrated system. This is a quite speculative assumption, and one which is unlikely to occur. The other option proposed, the adoption of a WS-based system, relies on a prototype technology that has been shown to work in a limited set of conditions, and doesn’t yet exist as a commercially available platform. Therefore, modelling of this option must assume some knowledge about its cost and that the technology will ultimately become commercially available, both of which are also speculative assumptions. Therefore, modelling of both pathways to controlled traffic vegetable production – tractor-based and WS-based – is subject to a number of assumptions about what might be possible.

Nonetheless, sufficient information is known about the soil, water, plant and mechanisation impacts of controlled traffic systems in other industries that it is not too difficult to apply some rules to modelling scenarios, and with a healthy dose of conservatism in assumptions made about the unknown, arrive at some indications of potential economic performance. Given the difficulty in accurately estimating many of the costs and returns associated with conversion to controlled traffic, all were treated very conservatively in the modelling reported in Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017). It is entirely feasible that the modelled economic performance of the controlled traffic systems under-estimate the true potential. Further, the key issue in such economic modelling is not reliance on the outputs as ‘the truth’, but rather to observe the relativity of outputs for different systems, and the capacity to identify which factors have the greatest influence on model outputs. In effect, modelling provides the opportunity to ask the ‘what if’ questions, rather than necessarily attempting to provide ‘the answer’.

Table 2 in the literature review (Chapter 2) provides a list of advantages and disadvantages associated with the adoption of controlled traffic. These all contribute, either positively or negatively, to the economic performance of controlled traffic systems. The issue from a modelling, or even case study, perspective is that it can be difficult to ascribed monetary values to many of these points. Modelling tends to deal only with those factors to which monetary costs or benefits can be allocated. Nevertheless, many of the benefits, while difficult to measure in monetary terms, contribute to other aspects of the system for which it is possible to estimate a financial benefit, such as improved yield, and reduced labour and machinery capital and operating costs. Factors such as timeliness improvements, and the impact they may have on achieving optimum crop sowing time, with potential flow on effects for yield, can be assessed in crop models (e.g. APSIM) although this was not part of the economic modelling reported in Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017).

Ultimately, the purpose of the modelling done was not to provide an irrefutable answer to the questions of the economic benefits of controlled traffic in vegetable production. The more useful questions addressed are:

- Is there any indication that controlled traffic offers economic benefits for vegetable production?
- What factors have the greatest influence on the economic performance of a controlled traffic vegetable production system?

Applying the modelling across a number of different case study farms allowed assessment of different farming scenarios and provided a greater degree of confidence in the results.

This modelling did not go beyond the farm enterprise to consider the impact of widespread controlled traffic adoption on the future of the vegetable industry or the broader societal consequences of such a change. Modelling of that scale was beyond the scope of the investigation reported in the papers in Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017).

5.4 Key modelling factors

Modifying machinery to accommodate controlled traffic can be a barrier to adoption. Tullberg (2008) quoted a figure of $40,000 for setting up grain industry machinery. At the time, this would have represented 5-10% of the capital cost of the machinery being modified, and more recent estimates suggest that a similar percentage impost is still current (T. Neale, Data Farming, pers. com.). Equivalent costs are difficult to estimate in a vegetable industry context, as there is little prior experience on which to base estimates. Harvesters tend to be very specialised and are not modified without good reason. In the modelling reported in Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017), an allowance of up to 30% of capital cost was made, although 10% was selected as the most common surcharge for modifications.

In the case of a new technology, such as the wide span, it is not possible to know the capital cost when it currently exists only as a prototype. As noted in Chapter 5 (McPhee & Pedersen, 2017), the manufacturer of the prototype expected its production-run cost would be no more per engine kW than a conventional tractor, which at the time the modelling was done was approximated by the relationship Cost ($A) = 1300 x engine power (kW) (J. McPhee, unpublished data). This advice provided a basis for cost estimation used in modelling, although a margin of 10% on top of that estimate was added to account for the uncertainties involved.

Notwithstanding the somewhat large capital costs associated with adoption of controlled traffic, there are also savings to be made in machinery, particularly in relation to tillage equipment. Chapter 4 (McPhee et al., 2015) highlights the predicted elimination of some tillage operations, many associated with powered implements, and commercial experience indicates a reduction in complexity of tillage implements, with much less reliance on powered implements under controlled traffic management (Kable, 2019).

Increased capital costs, while a concern at the time of investment, need to be considered within the perspective of the economic performance of the whole system. More than any other factor, improved crop yield was the key income-related determinant of improved economic performance, regardless of the metric used, in all of the controlled traffic systems modelled for the four case studies reported in Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017). There were two dominant expense-related influences on economic performance – modification costs for tractor-based CTF (or in the case of the WS, the capital cost of the technology), and less commonly, the potential impact on harvest costs due to the constraint of traffic movements during harvest operations. While controlled traffic may have a negative effect on field efficiency and timeliness due to traffic movement constraints (Bochtis et al., 2010; Bochtis et al., 2010), it is expected that operators would develop systems to counter these disadvantages in the event of controlled traffic adoption. Further, there are many other advantages to the system that would counter these added costs, although that might not be a valid argument for a contractor whose primary interest is to maintain the highest possible product output regardless of the impact on other parts of the system.

5.5 Comparison of farms and systems

A number of probability curves are presented in Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017) to illustrate the change in various economic metrics used to assess the different farming systems modelled for each case study farm. Figure 5-1 shows an alternative presentation of these data, encompassing all case study farms in the one graph, specifically for the Average Net Farm Return (%), defined as [Total Return – (depreciation + insurance)]/[Total machinery cost]. It is clear that in all but case study 4, various options of implementing CTF could improve median returns by 60-80% over current conventional practices.

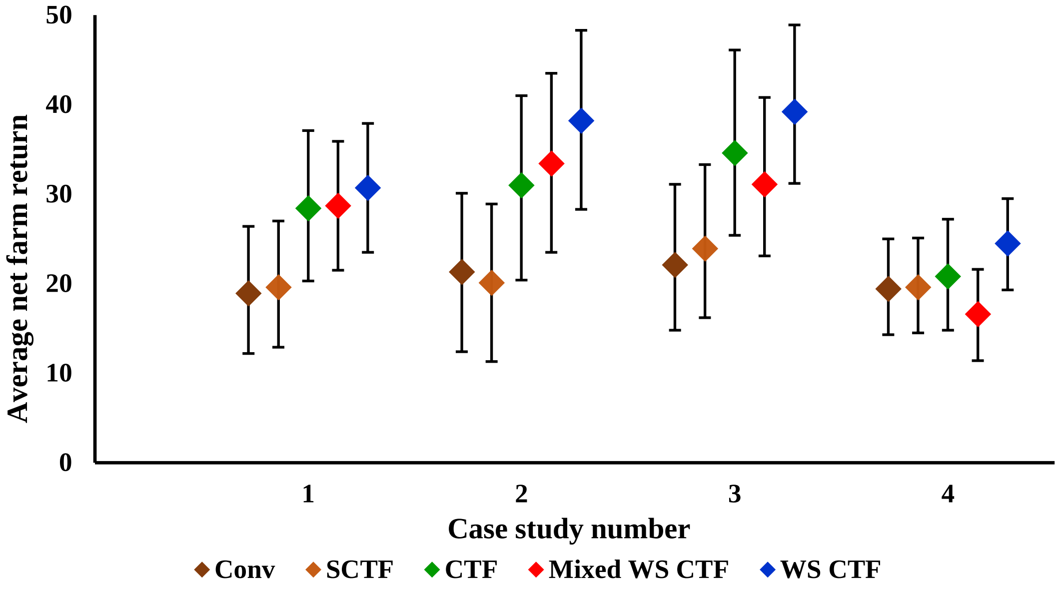

Figure 5-1. Average Net Farm Return for all case study sites. Marker = median value of all modelled scenarios, upper bar limit = 95 percentile values, lower bar limit = 5 percentile values.

5.6 Summary

By its nature, modelling relies on assumptions. The best that can be done to improve both the accuracy and relevance of a model is to use as much 'real' input data as possible and make the assumptions as accurate as possible. When faced with a scenario in which no 'real' data exist, such as the costs to modify machinery that is very difficult to change, or investment in machinery that is not yet commercially available, assumptions become all important. Taking a conservative approach to both the inputs and outputs in the modelling reported in Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017) provides some measure of confidence in the results, despite the uncertainties.

The modelling shows there are clear potential economic benefits despite the many unknowns related to adoption of controlled traffic for vegetable production. Realisation of those benefits is highly dependent on achieving higher crop yield, which has been shown to be possible over many crops in many production environments, and controlling the costs of machinery modification or re-investment.

CHAPTER 6. FUTURE DIRECTIONS

6.1 Background

The papers presented in earlier chapters highlight the mechanisation barriers to the adoption of controlled traffic in mixed vegetable cropping (McPhee & Aird, 2013), but also demonstrate significant potential benefits to be gained in terms of soil quality and operational efficiency (McPhee et al., 2015; Rodgers et al., 2018). Economic modelling showed that if access to suitable machinery could be achieved, significant benefits could be gained from the adoption of controlled traffic in the vegetable industry (McPhee et al., 2016; McPhee & Pedersen, 2017).

Wide-span (WS) tool carriers offer the opportunity for fully integrated controlled traffic in diverse cropping systems, such as mixed vegetable production. The potential is significant but so are the challenges, as the WS is a major departure from conventional approaches to mechanisation, such as the tractor, which has been the basis of mobile power since the early 19^{th} century. Wide span technology is not without precedent and has been proven within a limited range of circumstances over many decades. The first paper in this chapter describes the potential re-mechanisation of vegetable production based on the WS concept. As was detailed in the economic modelling reported in Chapter 5 (McPhee & Pedersen, 2017), the paper describes two approaches – one that uses the WS purely as a harvest platform integrated with conventional tractors and equipment, and the other that is entirely WS-based.

Referring back to Chapter 3 (McPhee & Aird, 2013), it is clear that the fundamental issue of machinery compatibility remains a challenge to the adoption of controlled traffic in mixed vegetable production. It is therefore important to contemplate if there are other options that could manage the impacts of traffic-induced soil degradation to deliver similar soil and productivity benefits as those that have been identified for controlled traffic. Progress in agricultural automation has led to the concept of integrated groups, or ‘swarms’, of light-weight machines for various field tasks. Compared to the large tractors and harvesters currently in use, soil compaction can be reduced with the use of smaller, lighter machines, leading to the view that light-weight swarm robots may provide an alternative to the challenges of adopting controlled traffic. Using a modelling approach, the second paper in this chapter explores the impact of light-weight harvesters on soil compaction and operational logistics and compares their potential to that offered by controlled traffic.

The two papers that comprise Chapter 6 are:

Pedersen, HH, Oudshoorn, FW, **McPhee, JE** and Chamen, WCT, (2016) ‘Wide span – re-mechanising vegetable production’, *Acta Horticulturae*, 2016.1130.83. XXIX IHC - Proc. Int. Symposia on the Physiology of Perennial Fruit Crops and Production Systems and Mechanisation, Precision Horticulture and Robotics, pp. 551-557. ISSN 0567-7572

McPhee, JE, Antille, DL, Tullberg, JN, Doyle, RB, Boersma, M, (2020) ‘Managing soil compaction –a choice of light-weight autonomous vehicles or controlled traffic?’, *Biosystems Engineering*, **195** (227-241).

The article above, ‘Wide span – re-mechanising vegetable production’, has been removed for copyright reasons

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Research Paper

Managing soil compaction – A choice of low-mass autonomous vehicles or controlled traffic?

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Modelling
Soil compaction

Compaction-induced soil degradation is of growing importance as field machinery continues to increase in power and mass. Approaches to managing the impacts of soil compaction include minimisation (reduce load), remediation (tillage) and confinement (control traffic). Integrated 'swarms' of low-mass autonomous machinery have recently been suggested as a means of reducing compaction and an alternative to controlled traffic. In this study, combine and potato harvester machinery relationships were used to predict the specifications of potential low-mass harvesters for use in soil compaction modelling. Results suggested that combine harvester gross vehicle mass (GVM) must be less than 6 Mg to keep the modelled soil bulk density below 1.4 Mg m^{-3}. With this constraint, 6–9 small harvesters (~50 kW) would be required to replace one Class 9 (>300 kW) harvester. A fleet of this size would require access to unloading facilities every 2.5–3 min for the modelled yield conditions. For root and tuber harvesting, which results in a high degree of soil disturbance, no low-mass harvester option was found that would avoid compacting the soil to unacceptable limits. Avoiding soil compaction while maintaining acceptable productivity will pose considerable design and logistics challenges for low-mass grain, root and tuber vegetable harvest machinery. The integration of controlled traffic farming (CTF) and medium-capacity autonomous machines (~10–20 Mg GVM for combine harvesters) may be a better solution for both soil compaction and operational logistics than low-mass swarm technology.

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Nomenclature

AIC	Akaike Information Criterion, a measure of goodness of fit of a model (Sakamoto, Ishiguro, & Kitagawa, 1986)
B	bin capacity (of combine harvester) (m^3)
BD	soil bulk density ($Mg\ m^{-3}$)
BD_c	Critical soil bulk density ($Mg\ m^{-3}$)
CLL	Crop Lower Limit (%, w/w) – soil- and crop-based parameter approximately equal to the laboratory determined Permanent Wilting Point at 1500 kPa (Huth, Bristow, & Verburg, 2012)
CTF	Controlled Traffic Farming
DUL	Drained upper limit (%, w/w) – soil- and crop-based parameter approximately equal to the laboratory determined Field Capacity at 33.3 kPa (Huth et al., 2012)
FC	Field Capacity (%, w/w) – laboratory measured soil water content at 33.3 kPa - (Hartge & Horn, 2016)
GVM	Gross Vehicle Mass (Mg)
M	mass of cutter bar header (Mg)
P	power (kW)
s.e.	standard error – $\frac{\sigma}{\sqrt{n}}$; where σ = standard deviation, n = number of observations
W	average cut width of combine harvester (m)
w	width of cutter bar header (m)
WL	Wheel Load (Mg) – the vertical static load on the wheel resulting from the portion of the vehicle mass carried by the wheel. (For the purposes of this paper, wheel load and tyre load are the same, with 'tyre load' being the terminology used when discussing constraints imposed by tyre specifications, such as inflation pressure and safe load.)
θ_g	gravimetric soil water content (%, w/w)

1. Introduction

Soil compaction in mechanised field-based cropping is widespread and its importance and occurrence is linked to heavy machinery traffic (Keller, Sandin, Colombi, Horn, & Or, 2019). The impacts of traffic-induced compaction on crop production attracted attention in the 1960s (Arndt, 1966; Cooper, Trouse, Dumas, & Williford, 1969; Flocker, Vomocil, & Timm, 1960) at a time when the mass of most tractors was less than 3 Mg. Many research papers have been published on the topic in the intervening decades (Batey, 2009; Håkansson & Reeder, 1994; Smith & Dickson, 1990; Soane, Dickson, & Campbell, 1982).

Productivity and labour efficiency requirements have seen cropping machinery increase in size, mass and power in recent decades. Combine harvesters with a fully loaded mass of 35 Mg are now common, and some self-propelled vegetable harvesters exceed 50 Mg when fully loaded. Increases in machine mass over the past 60 years have been linked to greater soil compaction, declining soil functionality, plateauing yield and increased flooding (Keller et al., 2019).

Compaction is both a depth and an area issue. Almost 30 years ago, traffic intensities of 220–250% were reported in European grain cropping and over 500% for root crops (i.e. the seasonal area of wheel tracks can be as much as five times the area of the field) (Domzal, Glinski, & Lipiec, 1991). Larger farms and wider equipment reduce traffic intensity (van de Zande, 1991) and more recent European studies indicate traffic intensities in grain production systems of 86–95% for conventional cultivation, reducing to 64–73% for minimum tillage and 56% for zero tillage (Kroulik, Kumhala, Hula, & Honzik, 2009; Masek, Kroulik, Chyba, Novak, & Kumhala, 2014). Similarly, traffic intensities of 82% when using conventional tillage and 46% for zero-till operations have been reported for Australian grain production (Newell, Jensen, & Walsh, 1998). Although higher capacity root crop harvesters with greater working width are now more common than 30 years ago, seasonal traffic intensity >200% is still common (J. McPhee, unpublished data).

There are three approaches to managing soil compaction in cropping systems, as discussed in Soane et al. (1982) and Raper and Kirby (2006):

- Minimisation – avoid traffic or reduce loading when soil is most susceptible to compaction (e.g. high soil water content). The benefits and limitations of low ground pressure tyres and tracks to reduce the impacts of traffic have been extensively reported.
- Remediation – use mechanical tillage or crop roots to relieve compaction after damage has occurred. Tillage for remediating soil compaction is as old as agriculture itself and has been widely researched. Interest in 'biological ripping' using deep rooted crops dates from at least the mid-1980s (Elkins, 1985).
- Confinement – adopt controlled traffic farming (CTF) so all heavy loads are carried on dedicated, compacted wheel tracks, leaving a high proportion of soil that is not impacted by traffic. Isolation of compaction through the use of CTF has been shown to provide superior soil benefits to minimisation or remediation (Dickson & Ritchie, 1996; McPhee, Aird, Hardie, & Corkrey, 2015). Controlled traffic can be implemented using technologies ranging from draught animals (Van Cooten & Borrell, 1999) to conventional tractors (Tullberg, Yule, & McGarry, 2007) and wide span gantries (Chamen, Dowler, Leede, & Longstaff, 1994).

An advantage of CTF is that it manages soil compaction whilst allowing the use of large, high-capacity equipment, a key benefit for timeliness and productivity. Advances in agricultural automation have led some to suggest that compaction could be managed with the use of integrated groups, or 'swarms', of low-mass machines that reduce, rather than isolate, traffic loads (Anon., 2018; Knights, 2018; Leonard, 2013; Maza et al., 1997).

Some guidance on the compaction effects of low-mass machines can be gained from Håkansson and Reeder (1994), who assert that driving a vehicle on moist, arable soil is likely to give measurable compaction to depths of at least 300 mm at an axle load of 4 Mg, 400 mm at 6 Mg, 500 mm at 10 Mg and 600 mm or deeper at axle loads of 15 Mg or greater. Advances in track and tyre technology in the decades since Håkansson and Reader's findings have provided more options to reduce the compaction impacts of load through appropriate design and selection of running gear, changing how the load is distributed on the soil (Ansorge & Godwin, 2008). Nevertheless, for a given soil condition and running gear combination, increased load generally leads to increased compaction. High axle loads and moist soil are common factors in agricultural field operations (e.g. fresh vegetable harvest mostly occurs on moist soil, often close to field capacity).

1.1. Objectives and scope

The objectives of this work were to:

1. use modelling to predict the changes in soil bulk density due to low-mass machine traffic
2. investigate the impact of critical soil bulk density limits on the mass and operational capacity of low-mass machines for two different harvest scenarios
3. identify machine sizes that provide the redundancy benefits (i.e. avoid single machine dependency) of multiple autonomous machines, minimise traffic-induced soil compaction and achieve acceptable productivity.

The study assessed the soil compaction and operational capacity characteristics of low-mass harvesters using machine parameter relationships and soil compaction modelling. The focus of this study was two common but different operations – grain and root or tuber vegetable harvest. Regardless of the crop, harvest usually entails the most significant materials handling of any farming operation, and hence the heaviest machinery. It is also often the most time-critical, with timeliness and logistics being key factors in the selection of machine capacity.

2. Materials and methods

2.1. Soil compaction models

Various models have been developed to simulate the impacts of vehicle traffic on soil compaction, including COMPSOIL (Defossez, Richard, Boizard, & O'Sullivan, 2003; O'Sullivan, Henshall, & Dickson, 1999), SoilFlex (Keller et al., 2015), SoilFlex-LLWR (Keller, 2005) and Terranimo (Terranimo World, 2019), an online tool based on SoilFlex. COMPSOIL was selected for this study as relevant soil data (BD – soil bulk density, and θ_g – gravimetric water content) were available. SoilFlex and SoilFlex-LLWR required soil characteristics that were not readily available. Terranimo allows the user to input specific soil data to a depth of 1 m, whereas we had data only to 0.8 m and 0.5 m for the two soils used in modelling. COMPSOIL estimates the propagation of stress in the soil while accounting for both rebound and recompression (Defossez et al., 2003; O'Sullivan et al., 1999). The model includes 'standard' data on two soil types (clay loam, sandy loam) with four descriptive soil water contents (dry, moist, wet, very wet) and four descriptive pre-traffic soil bulk density conditions (Seedbed, Harvest, Loose over Dense, Loose to Depth). The soil bulk density conditions represent those expected to be found in these soils and at these moisture contents before commencement of, respectively, seeding, grain harvest and traffic over soil cultivated to different depths (i.e. Loose over Dense, Loose to Depth). The BD and θ_g data for these standard conditions are available in the model. COMPSOIL has capacity to input data for other soil scenarios and is limited to a maximum wheel load of 10 Mg, which was not a constraint for this analysis. Modelling of tracks is not possible with COMPSOIL.

2.2. Site descriptions and preparation of soil data for COMPSOIL

Two agriculturally important Australian soils were chosen to model harvest operations – a Black Vertosol for rain-fed grains, and a Red Ferrosol for irrigated root or tuber vegetables (Isbell, 2002).

The Vertosol was located at Yargullen, Queensland (27° 28′ 36″ S, 151° 37′ 16″ E) and had been managed under a CTF regime for at least 6 years. Cores (40 mm dia.) were collected in 200 mm increments from 0 to 0.8 m depth, weighed, and dried at 105 °C for 48 h to determine BD and θ_g (McKenzie, Coughlan, & Cresswell, 2002). Pre-traffic BD and θ_g profiles used in modelling were determined from the average of 43 individual profile samples. The original data set for this soil was reported by Antille and Baillie (2019).

The grower's rotation was cotton-cotton-wheat-long fallow (12 months). Core samples were taken from the cotton plant rows at harvest of the second cotton crop. Cotton and grain machinery dimensions were integrated in a 2:3 ratio (i.e. 6 m cotton and 9 m grain working widths). The cropping rotation and machinery configuration gave a wheel track area of ~50%, which is high compared to typical CTF systems used in grain (Isbister et al., 2013). The use of satellite guidance and auto-steer ensured the sampling locations had not been subject to traffic impact across seasons. The BD of the non-trafficked soil was approximately 15% lower than that of another Black Vertosol that had been managed under a fully integrated CTF system (16% track footprint) for 20 years (Antille, Bennett, Jensen, & Roberton, 2016), indicating that despite the relatively high traffic footprint, the non-trafficked soil adequately reflected CTF conditions.

At the time of sampling, the soil water content of the Vertosol was 36.9% w/w (std dev = 3.4%). This is a considerably higher soil water content than would be expected for rain-fed grain harvest, the operation of interest in terms of modelling. Equations have been developed for a number of Australian Vertosols to estimate the crop lower limit (CLL) for wheat based on a measure of the drained upper limit (DUL) (Peake, Hochman, & Dalgliesh, 2010). The DUL of the soil, 45.1% w/w (std dev = 3.6%) averaged over the depth of the sampled profile, was used to calculate CLL, which was then used in modelling to represent a dry harvest, the most common scenario in the Australian grain industry. Soil bulk density responses to wheel loads were modelled to 0.5 m depth.

The Ferrosol soil profile was based on core samples collected at Forth, Tasmania (41° 12′ 04″ S, 146° 15′ 36 E). Soil cores (72 mm dia., 50 mm deep) were taken from 10 locations in the field at 100 mm increments to 0.5 m depth immediately after passage of the digging front of a top-lift carrot harvester and prior to the passage of the harvester tyre that tracks in the dug row. BD and θ_g profiles were determined from the average of the 10 individual profiles sampled using the same protocol as for the Vertosol. The depth of soil disturbance is similar for top-lift carrot and share lift potato harvest, so it was considered the soil conditions would be applicable to both styles of harvest operation for modelling purposes.

Field capacity (FC) data were not available for the specific site of the Ferrosol sampling, but data from similar soils in the region indicate the core samples were at approximately 80% FC when collected (M. Hardie, Senior research scientist, University of Tasmania, pers. comm) and considered to be representative of soil water content conditions for potato and carrot harvest during autumn, the main harvest season for those vegetables in Tasmania. For soil compaction modelling, the profile data were used at the measured field soil water content and a lower soil water content (~65% FC), calculated to provide an alternative soil condition considered to be representative of harvest conditions earlier in the season.

Bulk density (BD) and gravimetric water content (θ_g) values for the depths required for COMPSOIL inputs were obtained by interpolation after using MS-Excel® to fit a smoothed curve (scatter (x,y) with smooth lines command) to the average field profile data for each soil.

2.3. Determination of soil bulk density upper limit and safe loads for tyres

For a low-mass vehicle to be an effective alternative to CTF, its wheel loads must be sufficiently low to avoid the need for remedial tillage after harvest. Given this, we chose soil bulk density 'trigger values' as the upper threshold of acceptable compaction. Bulk density trigger values are often used as a soil quality indicator for assessment of environmental and agricultural soil conditions and are generally defined as the upper limit of BD that will support crop or enterprise productivity for a particular soil. It is suggested that BD less than the trigger value would not require remedial tillage for successful crop production. There is no fixed figure for BD trigger values, given the influence of several factors (e.g. soil texture, water content, crop to be grown etc.). We chose a band of 1.3–1.4 Mg m^{-3} as a critical soil bulk density range (BD_c) based on a review of several sources of information (Table 1).

The model was used to determine maximum wheel loads that could be tolerated without exceeding BD_c. Tyre sizes were selected to minimise soil stress, within the constraints of overall diameter <1500 mm, section width <320 mm and the lowest permissible inflation pressure (as defined in safe load tables) for the chosen tyre and load (TRAA, 2006). These tyre dimensions were chosen to be similar to those used on tractors and harvesters during early soil compaction research. The section width limit was also required to avoid situations in which the total width of two tyres might exceed the operating width of the harvesters. Details of tyres used in the modelling are given in Tables 2 and 3.

2.4. Machinery relationships

2.4.1. Combine harvesters

Desktop surveys of 63 cutter bar headers and 108 combine harvesters, ranging from 35 to 515 kW engine power, provided data to develop relationships between cutter bar header width and mass, and gross vehicle mass (GVM) and power, bin capacity and cut width. While a range of cutter bar headers may be used on a given combine harvester, sufficient details were available regarding header and harvester combinations to enable calculation of an average width (and hence mass) based on the combine harvester engine power. For combine harvesters, GVM = kerb mass + cutter bar header mass + full bin mass, assuming wheat bulk density = 0.77 Mg m^{-3}.

It was assumed that low-mass combine harvesters would be of similar design to existing grain harvesting technology, with a front-mounted cutter bar header, a grain bin and a 75:25 front:rear static mass distribution, based on industry data (PAMI, 2019). An alternative design concept with a 50:50 static mass distribution was also modelled for combine harvesters having the same maximum tyre loads as those chosen for the 75:25 design option. Since combine harvester bin capacity is a function of harvester mass (Fig. 1), the 50:50 design would provide greater carrying capacity than the 75:25 design for the same maximum wheel load.

Swarms of low-mass machines will need to at least match the operational capacity of existing systems. Many crop and machine factors influence combine harvester throughput and required capacity is very context-dependent. Yield monitor records from two Class 9 (>300 kW) combine harvesters operating in 12 wheat fields in two different growing environments (Queensland – John Deere S680; Tasmania – CLAAS Lexion 580) provided guidance on contemporary harvest rates.

Table 1 – Soil bulk density (BD) trigger values for cropping soils reported for a range of environments.

Country/soil type	BD limits (Mg m^{-3})	Source
UK/mineral and calcareous	<1.3 Mg m^{-3}	Merrington (2006)
NZ/range of soils	<1.2 Mg m^{-3}	Sparling, Lilburne, and Vojvodic-Vukovic (2003)
USA/silt loam	<1.3 Mg m^{-3}	Shukla, Lal, and Ebinger (2004) quoting Arshad, Lowery,
	<1.5 Mg m^{-3}	and Grossman (1996) and Lal (1994)
Argentina/Vertosol, Mollisol	<1.37 Mg m^{-3}	Wilson, Sasal, and Caviglia (2013)
	<1.44 Mg m^{-3}	
Australia/rehabilitated grey Vertosol[a]	<1.45 Mg m^{-3}	Antille, Huth, et al. (2016)

[a] 1.4 Mg m^{-3} was considered 'typical for a degraded Vertosol' in Australia (McHugh, Tullberg, & Freebairn, 2009).

Table 2 – GVM, mass distribution, tyre specifications, and individual tyre loads and inflation pressures used in soil compaction modelling for two axle, single tyre configurations on low-mass combine harvesters.

GVM (Mg)	Front:rear load ratio	Front tyre			Rear tyre		
		Designation	Modelled wheel load (Mg)[a]	Safe load (Mg)[b] @ inflation pressure (kPa)	Designation	Modelled wheel load (Mg)[a]	Safe load (Mg)[b] @ inflation pressure (kPa)
1.6	75:25	280/85R24	0.60	0.80 @ 60	200/70R16	0.20	0.34 @ 60
6.0	75:25	320/85R38	2.25	2.3 @ 260	280/85R24	0.75	0.80 @ 60
2.4	50:50	280/85R24	0.60	0.80 @ 60	280/85R24	0.60	0.80 @ 60
9.0	50:50	320/85R38	2.25	2.3 @ 260	320/85R38	2.25	2.3 @ 260

[a] Inflation pressures used in modelling were the same as those indicated for the safe load for each tyre.
[b] Load limits and recommended inflation pressures as defined in The Tyre and Rim Association of Australia Standards Manual (TRAA, 2006).

2.4.2. *Root and tuber vegetable harvesters*

Potato harvesters were chosen for the vegetable component of this study as relevant technical data were more readily available compared to harvesters for other in-ground vegetables. Potato harvesters fall into four distinct design 'families': 1) small three-point linkage tractor-mounted single-row harvesters; 2) tractor-towed direct-loading harvesters serviced by a chaser trailer for product receival; 3) tractor-towed bunker harvesters with on-board carrying capacity of 4–9 Mg; and, 4) self-propelled harvesters, usually with on-board carrying capacity of 6–15 Mg. There are very few small tractor-mounted machines in the market and technical specifications are not easily obtained. A desktop survey of 12 towed direct-loading, 13 towed bunker and 15 self-propelled harvesters provided information on number of rows, machine kerb mass, carrying capacity and power requirements (engine power for self-propelled harvesters, or minimum recommended tractor power for towed harvesters). The harvester configurations were two, three and four rows for direct-loading, one and two rows for towed bunker and two and four rows for self-propelled styles. For potato harvesters, GVM = kerb mass + carrying capacity, assuming potato bulk density = 0.66 Mg m^{-3}.

Yield monitor records from three towed bunker harvesters (two single row and one twin row) operating in 28 fields over two seasons in north-west Tasmania were used to provide guidance on the capacity performance expected of alternative harvest systems. These harvesters were operating in an undulating landscape with clay loam soils.

Table 3 – GVM, tyre specifications, and individual tyre loads and inflation pressures used in soil compaction modelling for single axle, single tyre configurations on low-mass root crop harvesters.

GVM (Mg)	Tyre		
	Designation	Modelled wheel load (Mg)[a]	Safe load (Mg)[b] @ inflation pressure (kPa)
0.8	300/70R20	0.3	0.58 @ 60
2.93	320/70R24	1.1	1.25 @ 160

[a] Inflation pressures used in modelling were the same as those indicated for the safe load for each tyre.
[b] Load limits and recommended inflation pressures as defined in The Tyre and Rim Association of Australia Standards Manual (TRAA, 2006).

2.4.3. *Statistics*

The linear model (lm) and anova functions in base R (R Core Team, 2019) were used to determine predictive models for grain and potato harvester parameters. Regressions for combine harvester data gave model equations of two generic forms, either $Y = aGVM + b$ or $Y = cGVM^2 + dGVM + e$, where Y is either power, carrying capacity or working width and GVM is gross vehicle mass. Similarly, data for cutter bar header width (w) and mass (M) gave an equation of the form $w = fM^2 + gM$; a–g are constants. The much smaller data sets available for potato harvesters, and the wide variation of key parameters within a given style of harvester (e.g. GVM and power for the same number of rows), resulted in relationships with relatively poor measures of statistical evaluation. As an alternative, a simple approach was taken whereby key factors, such as GVM row^{-1} and power row^{-1}, were calculated as the mean for each of the harvester styles.

2.4.4. *Assumptions*

For self-propelled machines, it is theoretically possible to have mass without power, carrying capacity or working width. Therefore, the relationship of these parameters to mass must have either a zero or negative y-intercept. Since negative power, capacity and working width are nonsensical, the x-axis intercept defines the minimum machine mass for $Y = 0$.

Models first had to pass a logical test based on this assumption. Regressions which gave an illogical intercept were rejected. Valid models were subsequently compared using Akaike Information Criterion (AIC) to determine the most appropriate choice. In cases for which there was little difference in the statistical evaluation of the various models, the simplest, logical option was chosen.

3. Results and discussion

3.1. *Grain harvest*

3.1.1. *Machinery relationships*

Analysis of data from the combine harvester desktop survey gave the relationships shown in Fig. 1(a–d). All regressions were significant at $p < 0.0001$.

Analysis of yield monitor data gave instantaneous yield and harvest rate (Table 4). Median (50th percentile) data were used for estimating the number of small combine harvesters

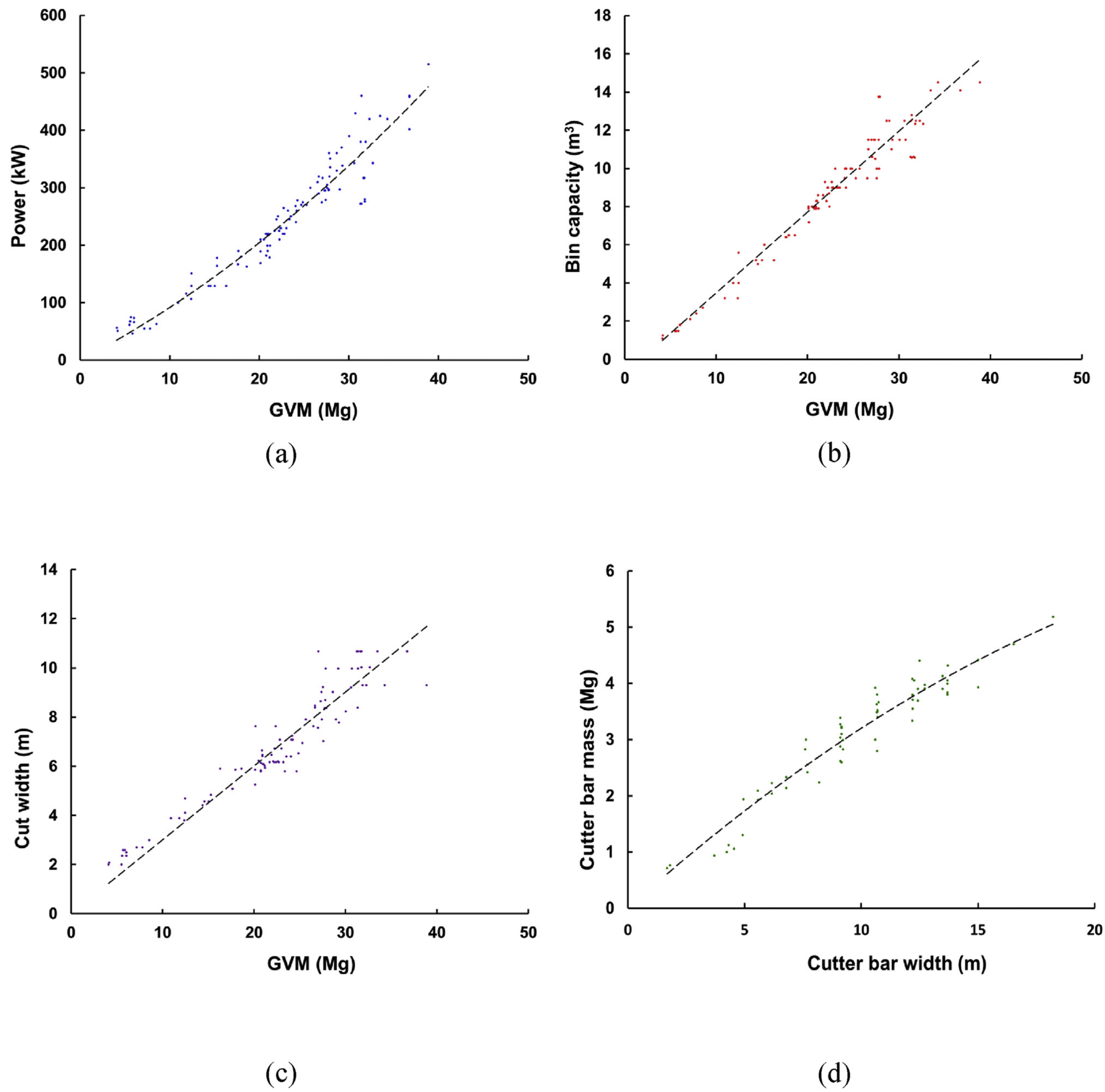

Fig. 1 – (a). Power (P, kW) – GVM (Mg) relationship for combine harvesters. ($P = 0.107GVM^2 + 8.081$, $R^2 = 0.918$. Relationship applicable for GVM >1.77 Mg); (b). Bin capacity (B, m^3) – GVM (Mg) relationship for combine harvesters. ($B = 0.423GVM - 0.747$, $R^2 = 0.936$); (c). Average cut width (W, m) – GVM (Mg) relationship for combine harvesters. ($W = 0.301GVM$, $R^2 = 0.910$); (d). Mass (M, Mg) – width (w, m) relationship for cutter bar header. ($M = 0.005w^2 + 0.372$, $R^2 = 0.928$).

required to meet current operating requirements. The range of instantaneous harvest system capacity demand is shown by the 1st and 99th percentile data.

3.1.2. *Soil compaction modelling*

The results of COMPSOIL modelling for the Vertosol at the CLL estimated that a GVM of 1.6 Mg (75:25) would limit soil bulk density to <1.3 Mg m^{-3}, the lower limit of the critical bulk density (BD_c) range defined in Section 2.3. A 6 Mg GVM (75:25) gives an axle load predicted to limit compaction to 0.4 m depth

Table 4 – Instantaneous wheat yield (Mg ha^{-1}) and harvest rate (Mg h^{-1}) calculated from yield monitor data from two combine harvesters operating in 12 different fields in two different growing environments.

	Tasmania			Queensland		
Percentile	1st	50th	99th	1st	50th	99th
Yield (Mg ha^{-1})	0.04	8.7	15.6	0.1	2.7	6.3
Harvest rate (Mg h^{-1})	0.20	31	45	1.0	28	42

(Håkansson & Reeder, 1994). The alternative 50:50 design was modelled for combine harvesters of 2.4 Mg and 9 Mg GVM, which respectively have the same maximum tyre loads as the 1.6 Mg and 6 Mg 75:25 design options.

Figure 2 shows the results of modelling for the Vertosol CLL soil water content conditions. The graph shows the θ_g profile and BD curves for pre-traffic soil conditions and two different wheel load scenarios for each combine harvester design, chosen to bracket the lower and upper limits of BD_c. The 'Harvest' condition (a standard pre-harvest traffic clay loam profile provided in COMPSOIL) is included for comparison. The GVM and wheel loads used in the modelling are given in Table 2.

While all loads increased BD from the pre-traffic condition, only 0.6 Mg wheel loads kept BD below BD_c in the upper regions of the BD curve. Initial bulk density is the main influence on changes to soil bulk density as a result of tyre load (Antille, Ansorge, Dresser, & Godwin, 2013), which may explain the relative decrease in BD in the zone immediately below the rut. This slight reduction coincides with a slight increase in BD in the pre-traffic BD curve, such that the magnitude of the change in BD from pre- to post-traffic is lower at this depth. The curves show quite high BD at depths greater than 0.3 m. Results at depths greater than 0.3 m should be treated with some caution, as O'Sullivan et al. (1999) acknowledged COMPSOIL output is sensitive to high soil water content, and will overestimate BD in some conditions. Even though this modelling was done at the CLL, the high DUL and clay content of the soil leads to calculated CLL soil moisture contents that are high compared to those used in the standard COMPSOIL profiles, particularly at depth.

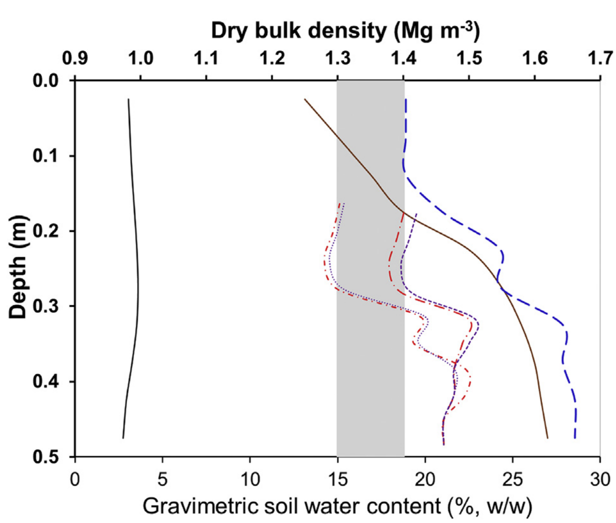

Fig. 2 – Pre- and post-traffic BD curves and θg profile for Black Vertosol soil water content conditions of a dry harvest under different wheel loads. 'Harvest', included for comparison, is a 'standard' clay loam profile included in COMPSOIL to represent soil conditions prior to grain harvest. Preceding numbers denote GVM (Mg). Numbers in parentheses denote wheel load (Mg). The ratio in parentheses denotes the front:rear load distribution of the combine harvester. The grey band represents BDc (1.3-1.4 Mg m^{-3}). Range of BDc (Mg m^{-3}); Harvest; Vertosol (pre-traffic); 1.6 GVM (0.6 WL) Mg (75:25); 6.0 GVM (2.25 WL) Mg (75:25); 2.4 GVM (0.6 WL) Mg (50:50); 9.0 GVM (2.25 WL) Mg (50:50); CLL (% w/w)

Table 5 – Predicted specifications of low-mass combine harvesters used in soil compaction modelling.

GVM (Mg)	Front tyre load (Mg)	Rear tyre load (Mg)	Engine power (kW)	Cut width (m)	Grain bin capacity (Mg, wheat)
1.6	0.60	0.20	13	0.5	<0[a]
6.0	2.25	0.75	52	1.8	1.38
2.4	0.60	0.60	20	0.7	0.21
9.0	2.25	2.25	81	2.7	2.36

[a] The lower GVM limit of 1.77 Mg (Fig. 1) indicates this combine harvester is nonsensical, as the bin capacity is <0.

The curves also demonstrate a considerable rut depth of 175 mm. By comparing the Vertosol model outputs with other COMPSOIL low BD profiles, it is apparent this is a function of soil BD, and hence soil strength, and the fact that the Vertosol shows no more than 1% variation in BD over the depth of the pre-traffic profile. The standard 'Harvest' soil used in COMPSOIL (O'Sullivan et al., 1999; Smith & Dickson, 1990) already had high BD over most of the profile depth, possibly due to historical traffic loads. In comparison, the pre-traffic BD of the CTF-managed Vertosol is considerably less than BD_c in the 0–0.5 m range.

3.1.3. *Harvest logistics*

The characteristics of the four combine harvesters in Table 5 were predicted from the relationships shown in Fig. 1. It is acknowledged that uniform mass distribution (50:50) combine harvesters, being a speculative design, may not follow the same power-mass-capacity relationships as current designs, but are included for comparison.

Figure 2 shows that for the Vertosol at CLL water content conditions, wheel loads should not exceed 0.6 Mg to keep soil bulk density below the lower limit of BD_c, and that the maximum wheel load should be 2.25 Mg to avoid exceeding the upper limit of the range. Referring to Table 5, the 0.6 Mg wheel load limit can only be achieved with a 75:25 design combine harvester that is less than the 1.77 Mg lower limit (Fig. 1), or a machine with uniform load distribution and carrying capacity of 0.27 Mg. The 2.25 Mg wheel load limit aligns with carrying capacities of 1.38 Mg for combine harvesters of current design and 2.36 Mg for a machine with uniform load distribution, based on wheat at 0.77 Mg m^{-3}. The smaller machines in Table 5 (1.6 Mg 75:25 and 2.4 Mg 50:50) would be totally impractical, as with tyre widths of 0.28 m, the minimum possible width of the machines would be wider than the cut widths of 0.5 m and 0.7 m. Therefore, these machines were excluded from logistics modelling considerations.

The impacts of the larger machine sizes on operational logistics are detailed in Table 6. Capacity requirements were calculated based on the median yield data in Table 4 and the relevant machine specifications in Table 5. Significant logistics challenges are associated with low-mass machines. As an example, there would be an unloading operation every ~2.5–3 min somewhere in the 6 Mg 75:25 combine harvester fleet, depending on the yield and harvest rate scenario. This would require either rapid turn-around of chaser bins, many chaser bins to service unloading cycles, or frequent departures from the field for a combine harvester to unload.

Table 6 – Operational requirements for low-mass combine harvesters capable of maintaining current instantaneous throughput and limiting soil bulk density of a CTF-managed Black Vertosol at CLL to 1.4 Mg m^{-3}, the upper limit of BD_c. Calculations based on field efficiency = 0.8 and median data from Table 4.

Front:rear load distribution	GVM (Mg)	Wheel load (Mg)	Operational requirements	Tasmania	Queensland
			Operating speed (m s^{-1})[a]	1.2	2.3
75:25	6.0	2.25 (front)	Number of units[b]	6	9
		0.75 (rear)	Bin fill time per unit (min)	15.9	27.0
			Average unloading cycle (min)[c]	2.6	3.0
50:50	9.0	2.25	Number of units	4	6
			Bin fill time per unit (min)	18.1	30.8
			Average unloading cycle (min)	4.5	5.1

[a] Median operating speed from the same data set that provided yield and harvest rate data in Table 4.
[b] Number of units has been rounded up to the nearest whole number.
[c] Average unloading cycle is the average time between individual unloading operations across the entire fleet. It reflects the cycle time for availability of an empty chaser bin, or for a unit to leave the field to unload.

One challenge of swarm harvesting is likely to be the timely provision of chaser bin capacity to unload combine harvesters. Chaser bins operating in a random traffic system must meet the same wheel load constraints as the combine harvester if compaction is to be minimised, suggesting their GVM restriction will be similar to the combine harvester. Depending on field size and travel distances, the chaser bin fleet to service a swarm of small combine harvesters on a ~2.5–3 min cycle time may well be larger than the fleet of harvesters.

Modelling suggests that the number of low-mass combine harvesters required to meet capacity requirements is sensitive to small falls in efficiency or travel speed. For example, a drop from 0.8 to 0.7 in field efficiency and a 10% reduction in operating speed for a 6 Mg combine harvester would add two harvesters to the required fleet for both scenarios presented in Table 6. This is an increase of 33% (Tasmania) and 22% (Queensland), indicating the sensitivity of the system to changes in operating conditions.

Yield variability is likely to assume more importance for small machines with limited grain carrying capacity. All combine harvesters face yield variation at the field scale, with up to 400-fold variation when measured at the instantaneous scale (Table 4). Large machines have substantial buffering capacity for this large range by virtue of their threshing and bin capacity. The ability of smaller autonomous machines to cope with yield variation will be heavily influenced by on-board storage capacity and the cycle time for return of chaser bins, as well as threshing systems designed to cope with such variations.

The modelling presents three key observations – 1) the CTF-managed Vertosol has 0.27–0.65 Mg m^{-3} lower soil BD than the COMPSOIL 'Harvest' soil profile; 2) there are severe limits on the mass of small machines in order to avoid compaction; 3) the mass and size limits have major implications for the logistics of harvest, with rapid unloading cycles being a key factor influencing swarm size and the provision of transport systems.

3.2. *Potato harvest*

3.2.1. *Machinery relationships*

Data from the desktop survey of potato harvesters resulted in the mean figures for power row^{-1} and mass row^{-1} shown in Table 7. It is a characteristic of potato harvester designs that machines with the same number of rows, even within a given design 'family', can have widely differing GVM and power requirements, as indicated by comparing the mean and the range of key machine characteristics in Table 7.

The direct-loading style was chosen for soil compaction modelling on the basis that, with no carrying capacity, it is the lightest of the designs. It is recognised that using data from two- to four-row harvesters to calculate the mean GVM row^{-1} will likely underestimate the GVM of a single row harvester, as the combined mass of the other components of a harvester (i.e. chassis, axle, outloading elevator) is not necessarily directly proportional to the number of rows. With an assumed load transfer of ~25% to the tractor drawbar (based on limited manufacturer data), a single row, single axle, two wheeled, 3.4 Mg harvester would have a wheel load of ~1.26 Mg. Drawing on a previous survey data set for tractor power-GVM

Table 7 – Mean GVM (Mg) and power requirement (kW) row^{-1} for different styles of potato harvester.

Design	Power (kW) or GVM (Mg) row^{-1}	Mean	s.e.	Range
Direct load,	Power[a]	45.2	3.5	45.0
towed (n = 12)	GVM	3.4	0.21	2.4
Bunker,	Power	48.7	3.1	34.5
towed (n = 13)	GVM	9.1	0.46	5.3
Bunker,	Power	115.3	5.1	51.5
self-propelled	GVM	11.9	0.54	6.4
(n = 15)				

s.e. – standard error.
[a] Data come from manufacturers' specifications and recommendations. Industry practice indicates tractors used on towed harvesters tend to have engine power 2–3 times manufacturers' recommendations. Tractor selection factors include mass for traction in variable digging conditions (e.g. slopes, wet soil) and drawbar vertical load capacity, particularly for bunker harvesters. Self-propelled harvesters use hydrostatic drives, so usable power is ~70–80% of the quoted engine power. These factors may partially explain the large difference in estimated power requirements per row, particularly between towed and self-propelled harvesters.

relationships (McPhee & Aird, 2013), the mean power requirement of 45.2 kW row^{-1} indicates a tractor of 2.6 Mg, having a wheel load of 1.2 Mg with the assumed load transfer of ~25%. As noted previously, industry experience suggests the tractor would need to be 2–3 times this GVM to function effectively, increasing the resultant wheel load to 2–2.7 Mg.

Analysis of yield monitor data gave yield and instantaneous harvest rate calculated on a per row basis (Table 8). The range of harvest system capacity demands is shown by the 1st and 99th percentile data.

3.2.2. *Soil compaction modelling*

Figure 3 shows the Ferrosol pre-traffic soil condition and the results of COMPSOIL modelling for two different wheel load scenarios and two different soil water content conditions as defined in Section 2.2. 'Loose to Depth' (LtD), a deeply loosened clay loam profile in COMPSOIL (O'Sullivan et al., 1999), is included for comparison. The wheel load conditions were 0.3 Mg and 1.1 Mg, chosen to bracket the lower and upper limits of BD_c.

Figure 3 shows that the pre-traffic state of the Ferrosol is below BD_c at all depths. In comparison, the 'Loose to Depth' profile used in COMPSOIL exceeds the lower limit of BD_c for depths greater than ~0.25 m. The BD curves for the 0.3 and 1.1 Mg wheel loads bracket the limits of BD_c for the 'dry' soil conditions (0.65 FC). The post-traffic soil bulk density for both wheel loads on moist soil (0.8 FC) exceeded the upper limit of BD_c at all depths and generated identical BD curves. Once again, this result should be treated with caution due to the sensitivity of COMPSOIL to high soil water contents (O'Sullivan et al., 1999).

3.2.3. *Harvest logistics*

Figure 3 suggests there is no practical safe wheel load for moist soil disturbed by root or tuber harvest. The wheel loads of 0.3 and 1.1 Mg represent harvesters of 0.8 Mg and 2.93 Mg GVM, respectively, assuming a two-wheel towed machine with 25% of the vertical load carried on the drawbar of the tractor. This is less than the 3.4 Mg row^{-1} average for current direct-loading harvesters, keeping in mind the prior comment that this is likely to be an underestimate.

The key functional requirement of a potato harvester is to dig, lift and separate tubers from a large volume of soil. In the case of the median yield of 56 Mg ha^{-1} (Table 8) this equates to ~85 m^3 ha^{-1} of tubers (tuber BD ~ 0.66 Mg m^{-3}) recovered from ~1500 m^3 ha^{-1} of soil (McPhee, Pedersen, & Mitchell, 2018). One indicator of the challenge this poses for low-mass machines is the average power requirement to move the digging share through the soil, which is approximately 18 kW per row (Johnson, 1974) at a speed of 0.8 m s^{-1} (the median speed from yield monitor data used in Table 8). The 18 kW per row average power requirement could easily be grossly underestimated for some situations, as there can be more than a two-fold variation in draught for different digging conditions (Johnson, 1974). This figure takes no account of power requirements for soil separation, product conveying or motion resistance.

This modelling suggests it will be difficult to design a root or tuber crop harvester that will meet the power requirements for digging and separation, whilst being light enough to avoid compaction of freshly dug soil. As no feasible option was found for a low-mass potato harvester, the analysis was not extended to estimate the numbers of smaller machines that would be required to replace current harvester capacity.

Table 8 – Instantaneous yield (Mg ha^{-1}) and harvest rate (Mg h^{-1}) per row calculated from yield monitor data from three potato harvesters.

	North-west Tasmania		
Percentile	1st	50th	99th
Yield (Mg ha^{-1})	5	56	125
Harvest rate (Mg h^{-1})	1.9	23.1	48.9

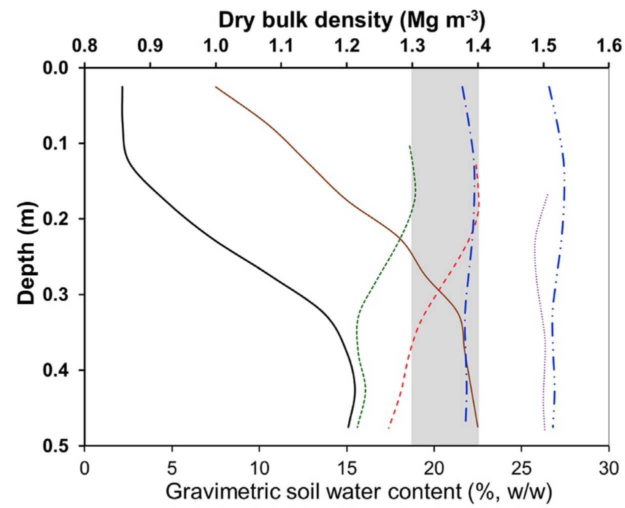

Fig. 3 – Pre- and post-traffic BD curves and θg profiles of a Red Ferrosol at two different soil water contents subjected to two different wheel loads. 'LtD' (Loose to Depth), included for comparison, is a 'standard' clay loam profile included in COMPSOIL to represent soil conditions following deep tillage. Preceding numbers denote GVM (Mg). 'All wheel loads' signifies that the resulting BD is the same for all loads at the higher soil water content of 0.8 FC. Numbers in parentheses denote wheel load (Mg). The grey band represents BDc (1.3-1.4 Mg m^{-3}). Range of BD_c (Mg m^{-3}); LtD; Ferrosol pre-traffic; All wheel loads, 0.8 FC; 0.80 GVM (0.3 WL) Mg, 0.65 FC; 2.93 GVM (1.1 WL) Mg, 0.65 FC; 0.8 FC; 0.65 FC

3.3. *Limitations and constraints of modelling process*

The conclusions reached in this analysis depend on estimation of several factors regarding machine power-capacity-mass relationships, design and performance requirements, measurement and estimation of soil properties, selection of an acceptable level of compaction and accuracy of soil compaction modelling. There are inevitable estimation limitations to all these factors.

3.3.1. *Harvester relationships, capacity and design*

Low-mass autonomous combine harvesters may be of an alternative design to that assumed in this work, but some functional requirements don't change. The combine harvester needs to gather the grain heads from the standing crop, separate the grain from the light fraction and convey it to temporary storage, either on-board or in a chaser bin for transport. Current combine harvester design has met industry requirements for many decades, and its success is evident in its application across a large range of machine sizes. Alternative designs may be possible, but there is currently little evidence of revolutionary change. The soil bulk density and logistics modelling results indicate the importance of load distribution when dealing with low-mass machines. Whilst acknowledging that the relationships presented in Fig. 1 may not apply to designs with uniform load distribution, there is potential for a 70% increase in carrying capacity for the 9 Mg GVM 50:50 design compared to the 6 Mg GVM 75:25 design for the same maximum wheel load.

Defining a low-mass root crop harvester is problematic. Harvester relationships (Table 7) indicate an approximate minimum power requirement per row, regardless of design. A single row harvester of 2.93 Mg GVM, the maximum to keep soil bulk density below the upper limit of BD_c in dry soil, would be some 15% lighter than the mean mass row^{-1} of current harvesters. While this may not seem like a large difference in machine GVM, it is important to reiterate that the mean GVM row^{-1} derived for potato harvesters will likely underestimate GVM for the single row configuration of any given design style. Further, the GVM of the tow tractor is likely to be 1.5–2 times the maximum harvester GVM required to meet soil compaction limits. Given the impact of draught, a lighter machine may not necessarily require significantly less power. While speed influences draught, so does the depth of operation of the digging share. It is proposed that low-mass machines will require a different approach to separating roots and tubers from soil in order to avoid the power requirements of moving large quantities of soil.

3.3.2. *Choice of soil compaction model*

O'Sullivan et al. (1999) acknowledge that COMPSOIL can both over- and under-estimate compaction in wet, soft soils, the general condition for the 'Loose over Dense' and 'Loose to Depth' profiles included in the model. Inspection of graphs in O'Sullivan et al. (1999) indicated overestimation of BD by ~20% in surface layers, and underestimation by ~5% in deeper layers, in a wet, soft soil. There is no suggestion that this issue applies to drier soils.

COMPSOIL was validated for a sandy and a clay loam in the UK (O'Sullivan et al., 1999). The Vertosol is a heavy clay soil throughout (~70–85% clay over the profile depth) while the Ferrosol has a clay loam topsoil (~40% clay) and clay subsoil (~60–80%). Differences in texture between the soils used in this modelling and the standard COMPSOIL soils are a potential limitation, particularly given differences in the nature of the clays in the Ferrosol and Vertosol. Ferrosols contain low reactivity clays and iron oxides, while Vertosols are reactive (shrink-swell) clays. The potential influence of textural differences has been noted by others, although it was accepted that the model output was indicative of the relative impact of traffic, despite the differences (Garrigues, Corson, Angers, van der Werf, & Walter, 2013; Joensuu & Saarinen, 2017).

3.3.3. *Choice of soil profile properties*

It could be argued that the use of a CTF-managed soil is an idealistic example of pre-traffic grain harvest conditions. However, we propose that if low-mass machines are to be considered as a means of managing soil compaction by virtue of limited soil stress impacts, they should be able to maintain soil conditions that are at least equivalent to those that can be achieved with an effective compaction management system already in use. Further, we propose that if 'conventionally' managed soils (such as the profiles included in COMPSOIL) are the compaction benchmark, soil loosening operations will be required. These will present a major challenge for low-mass machines with limited draught capacity.

The choice of a value range for BD_c is potentially problematic. Our approach to modelling was to treat $BD < BD_c$ as an acceptable result from the traffic of low-mass vehicles. However, a grower using a productive farming system founded on soils with a BD of ~1.0 Mg m^{-3} to 0.5 m depth (i.e. the Vertosol site) would question the logic of regressing to soil conditions with higher BD created by random traffic, even if caused by machines of low mass. In rain-fed production, even small reductions in porosity and pore continuity from compaction can have large impacts on infiltration and storage of plant-available water (McHugh et al., 2009).

Soil after root or tuber lifting has almost no bearing strength and avoiding all traffic compaction might also be considered an unreasonable benchmark to meet. All current designs of harvesters have tyres that run over freshly dug soil (Fig. 4). Regardless of whether alternative designs avoid this issue, low-mass harvesters and chaser bins will need to avoid driving on disturbed soil to avoid compaction.

3.4. *Factors other than soil compaction*

A large body of literature outlines whole-of-farm system benefits of CTF that extend well beyond soil compaction management and include improvements in a range of soil biophysical properties and productivity factors (Dickson, Campbell, & Ritchie, 1992; Kingwell & Fuchsbichler, 2011; McHugh et al., 2009; McPhee, Braunack, Garside, Reid, & Hilton, 1995; Neale & Tullberg, 1996; Neilsen, 2008; Rodgers, McPhee, Aird, & Corkrey, 2018; Tullberg, Antille, Bluett, Eberhard, & Scheer, 2018; Vermeulen, Tullberg, & Chamen, 2010). A selection of reported benefits include yield increases ranging from 0 to 95% (average close to 20%) in grain and pasture (Antille et al., 2019), 50% increase in available water capacity (McHugh et al., 2009), 90% reduction in soil erosion (Neilsen, 2008), almost two-fold increase in soil arthropod (Rodgers et al., 2018) and earthworm (Pangnakorn, George, Tullberg, & Gupta, 2003) abundance, 30–50% reduction in N_2O emissions (Tullberg et al., 2018), ~50% increase in dry land grain cropping profit (Kingwell & Fuchsbichler, 2011), ~30% reduction in implement draught (Tullberg, 2000), 20–60% fewer tillage operations (McPhee et al., 2015) and timeliness advantages ranging from days to weeks (McPhee et al., 1995). Aspects of CTF that could be directly compromised by the random and higher intensity traffic of low-mass harvesters include

Fig. 4 – Current towed, bunker-style single-row carrot (left) and potato (right) harvesters are designed with one tyre tracking over the top of the dug row immediately after product removal, resulting in very high compaction risk.

infiltration (Wang et al., 2008), energy use (Botta, Tolon-Becerra, Tourn, Lastra-Bravo, & Rivero, 2012) and in the case of grain cropping, the maintenance of standing stubble to facilitate inter-row and on-row grain crop seeding (Desboilles, 2017).

3.5. *Benefits attributed to low-mass autonomous machines*

Two benefits attributed to autonomous swarms are redundancy to avoid single-machine dependency and the potential for improved timeliness through 24/7 operation, having removed the need for operators. The many machines required to make a 'swarm' provide a high level of redundancy, while improving redundancy in current operator-based harvest systems would require not only more machines but also more operators.

For some harvest operations, the ability to work 24/7 is not a constraint. Harvest operations for grain (and many other crops) generally proceed for as many hours in a day as operating conditions allow. With current unautomated systems, this may require more than one shift of staff, but this would normally be preferable to losing working hours in the day, and the potential for yield or quality loss due to delayed harvest. Grain moisture and threshing efficiency are the usual limitations to continuing grain harvest operations. For root vegetable harvest, the limitations are often storage or transport capacity. Low-mass autonomous harvesters will generally only increase throughput if the cumulative capacity of the swarm exceeds the total capacity of current machines, as for any given harvesting situation, both systems would be constrained by the same environmental and post-harvest factors.

3.6. *The intersection of controlled traffic farming and robotics*

Industrial robots were first applied to repetitive manufacturing processes in defined spatial settings. Given the often-unstructured nature of field-based cropping environments, and the variability of agricultural products as compared to manufactured items, robotic applications in field-based agriculture have had to await the development of technology to cope with unpredicted variability, such as vision systems and artificial intelligence. We propose that using CTF will make the automation process considerably easier. Two defining characteristics of CTF are the dimensional integration of machines, and the establishment of permanent traffic lanes in the field (Baker et al., 2007). CTF introduces to field-based cropping a spatial framework that is predictable and repetitive, which must surely be advantageous to the development and adoption of autonomous machines (Fulwood, 2019).

While the separation of compacted traffic lanes from the soil used for growing crops has many advantages for the crop, it is important to also consider the benefits for machinery. From an automation perspective, lower BD soil in the absence of traffic leads to lower energy requirements (Tullberg, 2000) and potential reduction in machinery operations and inventory (McPhee et al., 2015). Further, compacted traffic lanes provide greater capacity to support loads (Monroe & Taylor, 1989) and improved timeliness (McPhee et al., 1995). These factors point to significant advantages in adding automation to medium-scale machines rather than focussing on low-mass, small capacity machines. In keeping with the harvest focus of this article, we propose that automation of medium-sized combine harvesters (~10–20 Mg GVM) would provide a balance between capacity and redundancy, and incorporated into a CTF system, would pose no risk of soil compaction in cropping zone soils. However, it is important to be aware of the ratio of tyre size to cut width. For example, 600 mm section width tyres on a 6 m cut width combine harvester result in a tracked area of 20%, compared to 10–15% for many larger machines currently in use.

Based on previously outlined machine relationships, combine harvesters of ~10–20 Mg GVM, of which there were many options in the 1980–90s, would provide grain carrying capacity of ~3.5–8 Mg and a cut width of ~3–6 m. Current single combine harvester throughput expectations could be met by a fleet of 2–7 machines (based on yield and throughput scenarios used in this work) with the benefit of unloading cycle times that are five times longer than those indicated in Table 6 for low-mass machines.

The situation for root and tuber harvest is less clear. Harvesters capable of CTF operation are virtually non-existent in the vegetable industry. A potential solution for CTF in the vegetable sector is the wide-span gantry (Pedersen, Oudshoorn, McPhee, & Chamen, 2016). The operational fundamentals and production benefits of wide-span technology for arable cropping were proven in the 1990s (Chamen, Watts, Leede, & Longstaff, 1992), although commercialisation for widespread use in the grain or vegetable industries has not eventuated. Automation of this technology should be no more difficult than automation of any other field-based machinery and would be simplified through operating in a CTF environment. A potential pathway forwards for the vegetable industry can be found in the medium-sized (5.7 Mg kerb mass), autonomous DOT tool carrier (DOT Farming Reimagined, 2019). Although not specifically designed for use as either a wide-span or for CTF, it has the basic design features to achieve both.

3.7. *Opportunities to improve modelling*

There are recognised limitations to the soil compaction modelling done in this work, highlighting areas which could be improved through research to enhance investigations of this nature. These include:

- better representation of soils with high clay content
- recognition that modelling in the context of low-mass machines must be done with due consideration of soil properties relevant to existing soil compaction management systems, such as CTF, not those exhibiting the effects of historical compaction
- capacity to accommodate tracks and more recent tyre designs, such as IF/VF (Improved Flexion/Very High Flexion) tyres.

4. Conclusion

1. For the soil textures, water contents and bulk densities commonly found during harvest of CTF-produced grain and conventionally produced tubers and roots, the wheel loads of autonomous harvesters and other support vehicles would have to be <0.6 Mg (grain) and <0.3 Mg (root crops) to limit soil bulk density from random traffic to less than BD_c (1.3 Mg m^{-3}).
2. Achieving a functional balance between operational capacity and limiting soil bulk density to less than BD_c will be a significant challenge, made more difficult if trying to emulate soil conditions that can already be maintained using high capacity machinery and CTF.
3. There is considerable scope to apply automation to medium scale machinery (~10–20 Mg GVM in the case of combine harvesters) operating in CTF systems to gain synergies for both soil management and productivity.

Peer-reviewed literature and popular media regularly report on the challenges of soil degradation in the context of changes required to feed the increasing global population over the next 30 years. It is proven that large machines cause soil compaction in field-based cropping and that CTF is an effective system for managing compaction and improving productivity, environmental sustainability and resilience. Small machines impose lower soil stresses than heavy machines, so it is valid to claim that low-mass autonomous machines will reduce soil compaction. However, to reduce soil compaction to levels achieved by CTF while maintaining machine capacity will be challenging. Given the urgency of arresting global soil degradation, we suggest rapid adoption of CTF, along with changes to equipment design where required, such as in annual horticulture. This will offer a much faster pathway to soil and production sustainability than low-mass autonomous vehicles, many of which remain conceptual. In the context of soil compaction and redundancy management, automation would be best applied to multiple machines of medium capacity (and hence mass) operated in the predictable spatial environment of a CTF system. Analysis indicates this could be achieved with combine harvesters of ~10–20 Mg GVM. There appears to be no other option than to re-design tuber and root harvesters to operate in a CTF system in order to avoid soil compaction.

Disclaimer

Mention of commercial brand names is for the purposes of clarity and does not imply support or endorsement of mentioned products in preference to similar machines.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.biosystemseng.2020.05.006.

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6.2 Discussion

The mechanisation challenges of adopting controlled traffic in mixed cropping have been outlined in Chapter 3 (McPhee & Aird, 2013). To a large extent, these challenges come down to differences in harvest machinery, which in turn are determined by factors such as crop type, crop architecture, spatial arrangement and mechanisms for collecting the harvested part (McPhee et al., 2018). The impacts of these differences are exacerbated when a wide variety of both vegetable and combinable crops is grown. The challenges confronting controlled traffic uptake extend beyond machine diversity to include ownership arrangements, as harvest operations are overwhelmingly undertaken by contractors with little to gain from investing in machinery modifications, or alternative designs, to facilitate the adoption of controlled traffic.

Machine design also has implications for the functioning of field layout, particularly with respect to issues such as erosion management. Even if modification of the entire machinery suite to a conventional tractor-compatible track gauge of 2-3 m was deemed possible and acceptable, the total area of permanent wheel tracks would still represent 30% or more of the field. While this is a considerable improvement on the ~500% of seasonal traffic that may be present in vegetable production systems (Domzal et al., 1991; Kuipers & Zande, 1994), the presence of such a large area of exposed compacted traffic lanes in undulating landscapes may be a significant erosion risk (Hagny, 2005).

Despite the challenges, the potential productivity and sustainability benefits of adopting controlled traffic in vegetable production are considerable. In the context of the research reported in Chapter 4 (McPhee et al., 2015; Rodgers et al., 2018), those benefits include reductions in tillage requirements and improvements in soil structure, infiltration, yield and soil biology habitat. While yet to be proven extensively in the field, economic modelling reported in Chapter 5 (McPhee et al., 2016; McPhee & Pedersen, 2017) points to significant potential improvements in farm business performance. Many other benefits have been reported from other industries and areas of research, including reduced nitrous oxide emissions (Tullberg et al., 2018), improved cropping reliability (McPhee et al., 1995c) and lower operating and ownership costs of machinery (Carr et al., 2008; Halpin et al., 2008).

Given the wide range of potential benefits from controlling traffic in crop production systems, it is logical to contemplate how the challenges present in mixed vegetable production, particularly those related to mechanisation integration, may be overcome so the industry can achieve profitability and sustainability gains through the adoption of controlled traffic.

The potential of wide span (WS) technology is first raised in the discussion of mechanisation barriers to vegetable industry controlled traffic adoption in Chapter 3 (McPhee & Aird, 2013). Chapter 5 (McPhee & Pedersen, 2017) considers the economic potential of the WS as a possible CTF solution, which is discussed further in Chapter 6 (Pedersen et al., 2016). The option of using autonomous swarms of light-weight vehicles, as an alternative means of addressing soil compaction has been addressed in Chapter 6 (McPhee et al., 2020).

6.3 Track gauge commonality

As emphasised throughout this thesis, integration of track gauge and working width are essential for the successful implementation of controlled traffic. This doesn't mean that all dimensions need to be the same, but they do need to integrate in a sensible fashion. For tractor-based systems, this generally means all vehicles will have the same track gauge and implements will be some multiple of that dimension. For example, most grain CTF systems are based around the harvester track gauge (~3.0 m) because the harvester is the most difficult machine to modify. Tractors, sprayers, chaser bins and seeder carts are adjusted to match (Tullberg et al., 2007), and 1:2:3 ratios are common – e.g. 12 m cut width harvester, 24 m seeder, 36 m sprayer (Isbister et al., 2013). In the cane industry, the biggest improvement has been made by altering the crop row configuration to match existing harvester dimensions (usually 1.8 m track gauge) and adjusting other machines to suit (Poggio et al., 2007).

As noted in Chapter 3 (McPhee & Aird, 2013), the range of harvesters used in the vegetable industry, and their diversity of design, makes it difficult to choose a common track gauge or working width on which to base a controlled traffic system. Specific instances of controlled traffic adoption are noted in the Chapter 3 discussion, namely those of Harvest Moon (Kable, 2019) and Mulgowie Farming Company (Johanson, 2020). Both rely on specific machinery modifications to suit the circumstances of the particular production system. While these solutions could be applied to similar circumstances, neither is a generic solution applicable to all crops or situations. There is no track gauge that could be adopted in the Tasmanian vegetable industry which would not require changes to equipment working width or crop spatial arrangement for some aspects of the rotation. One option which would provide a common track gauge for all machines and operations, whilst minimising the area of land sacrificed to wheel tracks, is the wide span (WS), as outlined in Chapter 6 (Pedersen et al., 2016).

6.4 Wide span

6.4.1 The steam era

The wide span concept is not new. The first published report of wide span development was by Halkett (1858) who noted that "This invention consists in the application of motive power to the cultivation of the land, by attaching the implements required for the various operations of ploughing, scarifying, sowing, hoeing, reaping or other operations of culture, beneath a travelling carriage, which moves on rails placed in parallel lines across the fields to be cultivated, by which the implements are always kept from swerving to the right or left of the line of onward motion, and the friction of the machinery is considerably reduced". Halkett was very aware of the benefits of improved traction and lower rolling resistance to be obtained by confining traffic to specific laneways, which in his system were parallel rails permanently placed in the field (Figure 6-1 and Figure 6-2).

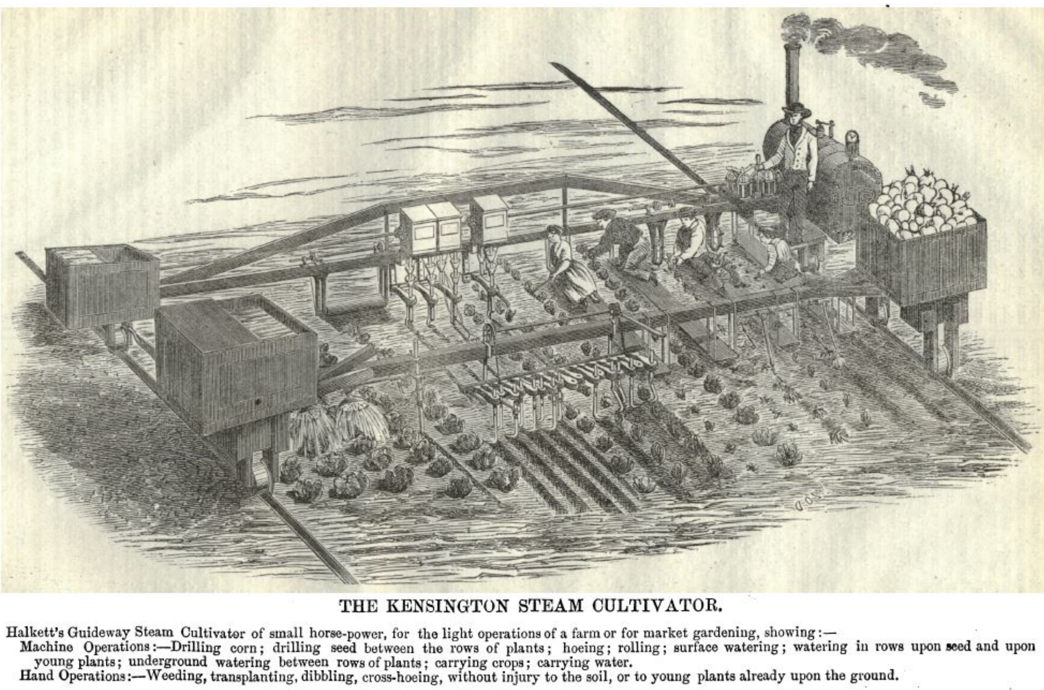
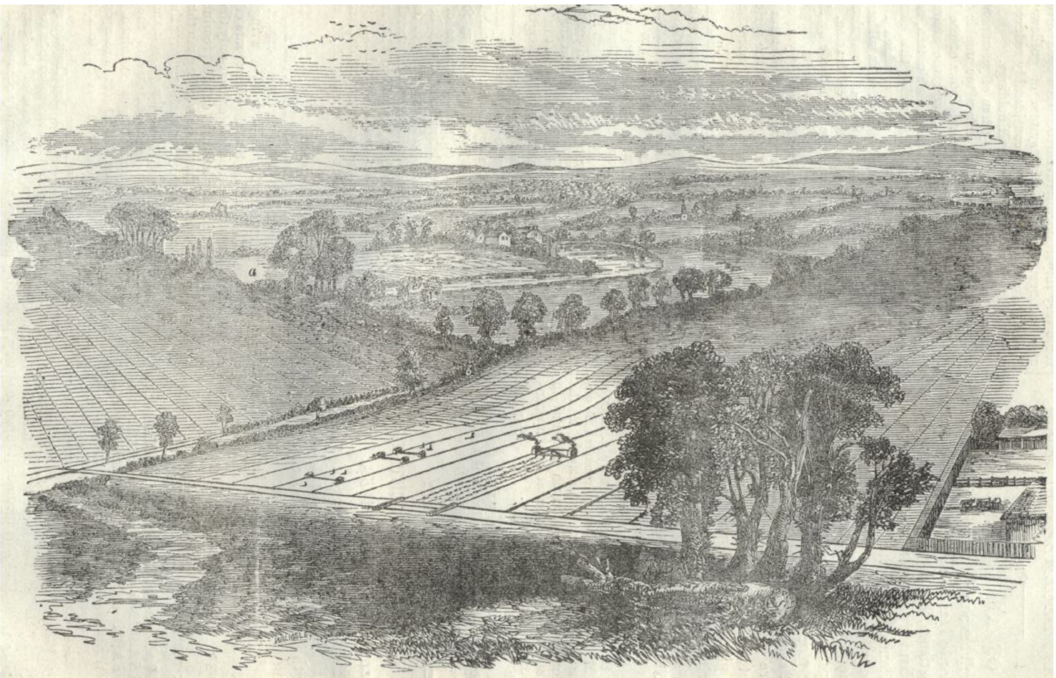


Figure 6-1. The Kensington Steam Cultivator as reported and illustrated by Halkett (1858).



View of a Farm laid down with Guideways, showing the Cultivator ploughing; a number of trucks taking off produce; the headland rails upon which the Cultivator is moved from one set of rails, or from one part of the farm to another, and a level crossing at the road, to enable it to communicate with the adjoining fields.

Figure 6-2. Field layout of tracks for the Kensington Steam Cultivator as reported and illustrated by Halkett (1858).

While controlled traffic was not a terminology used at the time, Halkett was aware of other benefits to be achieved by isolating traffic from the crop production soil, such as:

- Lower draft – "…the small amount of force with which the 12 ploughs were drawn through the ground …… will show how, when the cultivation of a farm is carried on without any operation treading upon the ground, we may expect that ploughing and other acts of cultivation will be performed …. at much less draught and power, and at much less expense….".

- Preservation of soil condition and plants – "the soil having thus been brought to a higher state of cultivation than it is possible to produce even with spade labour, there can be no difficulty in keeping it in that condition, for …. by the guideway system of steam culture, the whole weight of the machinery, …. rests upon the rails, …. nothing touches the soil except the implements in operation; no horse will poach the ground with their iron-shod feet; the footprints of the guide and ploughman will nowhere be seen pugging the clay and treading into a solid clod that which has been reduced to the fineness of garden mould." Further, "By the avoidance of walking amongst plants for that purpose (of planting, cross-hoeing etc.) no consolidation of the ground or breaking of the young plants can take place; and the soil is always in a loose and friable state".

- Accuracy of operations – "The destruction of weeds …. among growing crops, can only be performed at present during the earlier stages of the growth of the plant, and unless executed by hand labour are always attended with difficulty …. from the impossibility of guiding the implements …. to operate in sufficient proximity to the plant, without running into and destroying some portions of the crop. By this system …. I am enabled to adjust the implements and cause them to travel at the requisite proximity to the rows at all times during the periods of growth of the plant."

In a prescient comment on the negative impacts of root crop harvest, Halkett reported observations from a market gardener who remarked, "The crops can be carried without injury to the soil, for carrying crops and distributing manure are two operations very difficult to appreciate, as there are many who have grown large root crops, and suffered greatly from the removal of those crops."

Of note in relation to Halkett's gantry is that approximately 5% of the land area was devoted to the rails, a smaller portion of land sacrificed to traffic than any current CTF system. Detailed financial analysis and records of observations from contemporaries indicate that the steam guideway system was built and used, although the extent of its application or further development is unknown (Halkett, 1858). A contemporary of Halkett, Henry Grafton, reported in 1860 on a "System of Steam Culture" in which a steam-driven gantry traversed the field on "well-worn paths where the soil was packed firm" (Taylor, 1994). Whether or not Grafton's gantry (Figure 6-3) was ever built is not recorded.

Avoidance of the inevitable damage to soil by heavy steam-powered machines, with their low power-weight ratio, seems to have been a driving factor in the interest of wide span steam agriculture in the mid-1800s. The arrival of the internal combustion engine, providing more power in much lighter machines, appears to have signalled the end of an era of interest in gantries as the basis for mechanised agriculture.

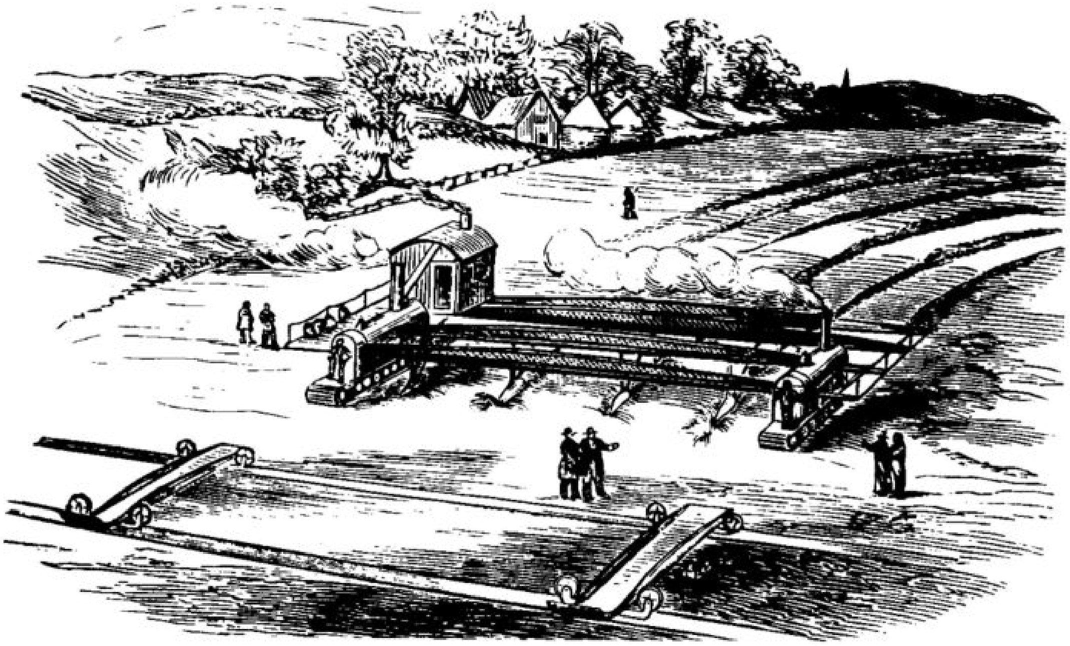


Figure 6-3. The Grafton System of Steam Culture as reported and illustrated in Taylor (1994).

6.4.2 The modern era

A review by Taylor (1994) indicates that interest in gantries next surfaced in the USSR in the 1950s. Most interest in gantries was as harvest aids, with little attention given to the potential of a fully developed production system based on the technology. Various gantries were developed for soil and agronomic research purposes through the 1960s - 80s (Gebhardt et al., 1982; Monroe & Burt, 1989; Sudduth et al., 1989; Taylor, 1994; Tillett & Holt, 1987). Commercial interest peaked in the 1980-90s with the development of the 6 m span FPU (Field Power Unit) by Ashot Ashkelon Industries Ltd. in Israel (Taylor, 1994) and the 12 m Dowler gantry (Chamen, Dowler, et al., 1994) in the UK (Figure 6-4 (a) and (b)). A number of factors appear to have driven the interest in gantries, including soil management, energy saving, reduced crop damage and opportunities for electrification and automation (Chamen et al., 1992; Hilton, 1986; Holt & Tillett, 1989; Manor, 1995). The most extensive evaluation yet reported of the potential of the gantry for field-based crop production was undertaken at Silsoe Research Institute (Chamen, Audsley, et al., 1994; Chamen et al., 1992).

(a) (b)

Figure 6-4. Attempts at commercialisation of wide span gantries in the 1980-90s included (a) the Dowler gantry and (b) the Ashot Ashkelon Industries Ltd Field Power Unit (FPU). (Source: W.C.T. Chamen)

The next effort at commercial use of wide span gantries came from ASA-Lift, a Danish manufacturer of root, tuber and bulb harvest equipment (Pedersen et al., 2015; Pedersen et al., 2013). This prototype WS (ASA-Lift WS9600, with 9.6 m track gauge, Figure 6-5) was used as the basis for the economic modelling presented in Chapter 5 (McPhee & Pedersen, 2017) and the assessment of its potential application for vegetable production is outlined in Chapter 6 (Pedersen et al., 2016).

Figure 6-5. ASA-Lift WS9600 prototype gantry, Denmark, 2015. (Source: J. McPhee)

6.4.3 Characteristics

The wide span is effectively a tool carrier. A WS-based production system would require attachment of all working implements, regardless of whether they were used for seedbed preparation, seeding, materials application or harvest, to be modified to mount on the wide span. In the mixed vegetable and combinable crops industry, implementing a WS system, complete with modified implements and attachments, would represent a significant degree of change. However, it is proposed this would be no more difficult than trying to find a commonly acceptable track width, and appropriate working widths, across the range of machines currently in use, and then achieving the necessary mechanical modifications to effect change across the entire industry.

There is one operational characteristic of wide spans that is particularly relevant to the incorporation of existing implements into a WS system, and this is its ability to operate with partial working widths. There is a common misconception that a WS needs to operate on a full-width basis. While this may be efficient in terms of work rate, there are limitations to such a requirement for some operations. Using potato harvest with the ASA-Lift WS9600 as an example, there is a substantial difference in the distance that could be travelled to fill an on-board bunker if the machine was digging full width (~9 m) compared to current Tasmanian industry practice of digging one or two rows in a pass (~0.8-1.6 m). It is entirely feasible to fit a WS with a partial-width digging front, which may be indexed across the frame for successive passes along the same wheel tracks, without concern for offset draft loads (Chamen, et al., 1994). As the power supply to each drive wheel is independent (i.e. not mechanically linked, being either hydraulic or electrical), the turning moment of offset draft loads can be countered by supplying more power to the drive wheels closest to the load. In terms of simplicity, the easiest partial width arrangement to use on a WS is 50%. This would allow the WS to travel from one end of the field to the other working half of the span width, effect a pirouette turn at the end of the run, and return on the same wheel tracks to work the other half of the span without having to index the implement along the span structure.

Many tillage and seeding implements used in the vegetable industry are three-point-linkage (TPL) mounted. Early versions of the Dowler gantry (Chamen et al., 1994) and the more recent ASA-Lift WS9600 (Pedersen et al., 2016) featured standard linkage arms suitable for mounting conventional equipment. Mounting of a partial-width cereal harvester (Chamen et al., 1994) demonstrated a concept that could be applicable to existing vegetable harvest machinery (e.g. peas, beans) to allow integration with a WS. The prototype ASA-Lift WS9600 was designed to enable mounting of light tillage equipment and two onion harvesting heads that covered two-thirds of the span. The remaining third of the span was harvested by a return pass on the same wheel tracks using only one harvesting head as illustrated in Chapter 6 (Pedersen et al., 2016). The onion harvesting option demonstrates a concept that could be applied to any root or tuber harvesting operation.

While there would be considerable change required to integrate the WS into vegetable production, historical and more recent efforts suggest that many of the machinery changes required are, at least conceptually, within the bounds of current implement and harvester design. The modifications required would be less about radical changes to machine design, and more a re-arrangement of existing, proven components. The pictures shown in Figure 6-5 illustrate conceptually the specific components that could be taken from existing harvest technology and adapted for mounting on a WS tool frame with the capacity to carry produce either in an on-board bin or bunker or off-load it to a chaser vehicle.

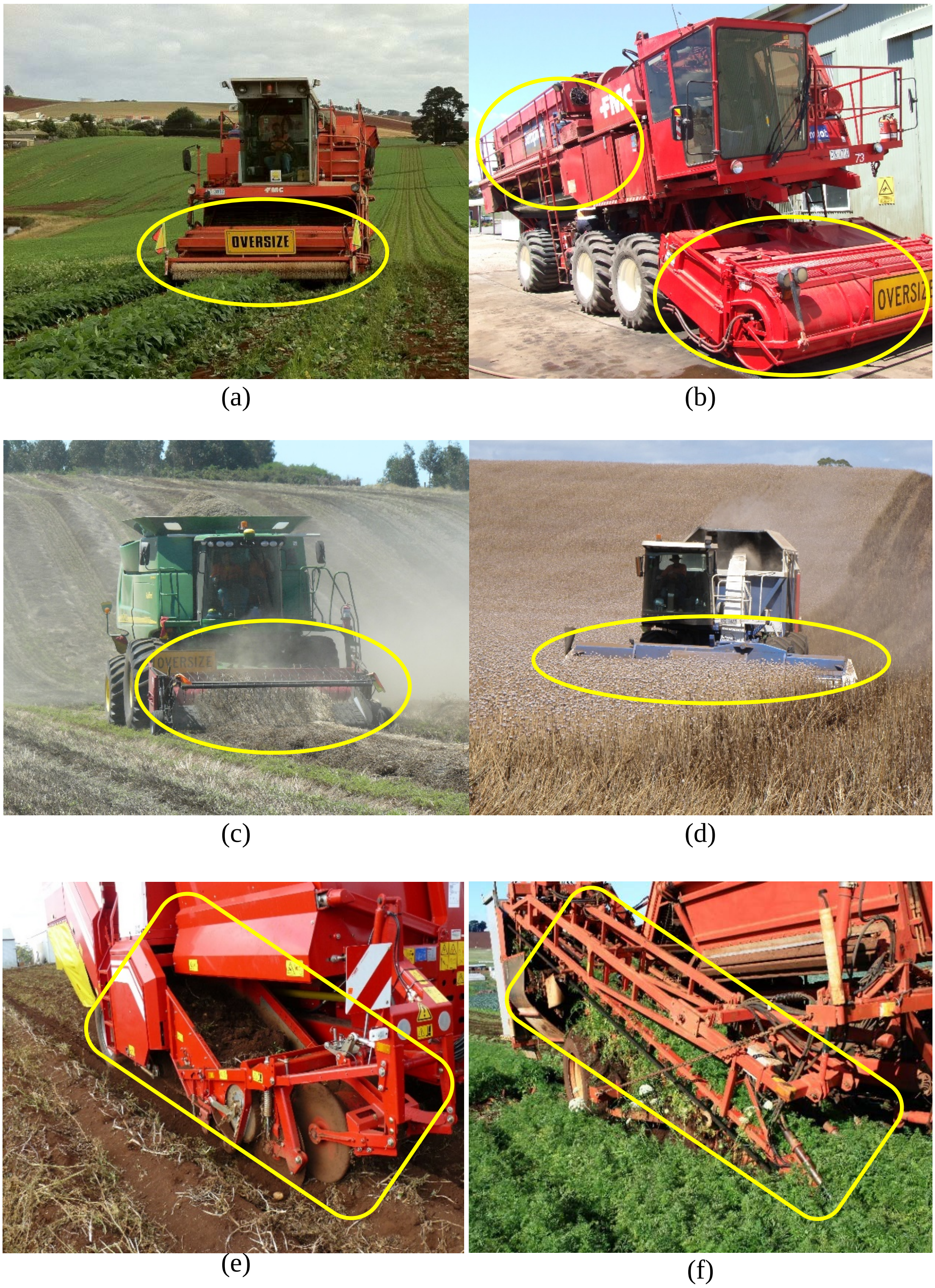


Figure 6-6. Crop collection components of existing harvesters that could possibly be adapted for use on a WS harvest tool carrier – (a) bean front, (b) pea front and viner, (c) pyrethrum windrow front and thresher, (d) poppy front and mulcher, (e) potato digger, (f) carrot top-lifter. (Source: J. McPhee)

Further, as an interim step towards WS-based controlled traffic, Chapters 5 (McPhee & Pedersen, 2017) and 6 (Pedersen et al., 2016) outline an option for mixed systems employing conventional tractors and implements for in-season work, and a WS for harvest operations. Figure 6-6 shows a conventional tractor with axles extended to 3.2 m to match with the ASA-Lift WS9600, which spanned three crop beds each 3.2 m wide. Such an approach would address the issue of the dimensional incompatibility of harvesters across a range of crops while reducing the need to initiate wholesale re-mechanisation at the outset. Conversion of conventional tractor-based operations, such as tillage and seeding, to a complete WS system could be approached at a later stage, after the soil-induced benefits of CTF adoption had started to become evident. Such a staged approach would build confidence in the development of alternative approaches to tillage and seeding based on improved soil structural conditions.

Figure 6-7. Conventional tractor with axles extended to 3.2 m to work in conjunction with the ASA-Lift WS9600. (Source: J. McPhee)

6.5 Light weight autonomous machines

Whereas the adoption of controlled traffic in the grain industry is often perceived to be more complex and expensive than is actually the case, preceding discussion suggests that complexity and cost are significant challenges to the use of controlled traffic in mixed vegetable production. Given this state of affairs, it is perhaps useful to investigate alternatives to controlled traffic for improving soil management and productivity in the industry.

Progress in agricultural automation has led many to question the need for large, high capacity machinery, proposing instead that capacity, timeliness and redundancy can be enhanced with the use of integrated groups, or 'swarms', of light-weight machines for various field tasks. Further to the work functions required, minimisation of soil compaction is often promoted as an advantage of swarm robotics, with the minimal impact of light-weight machines offering an alternative to the cost and complexity of adopting controlled traffic (Anon., 2018).

The peer-reviewed literature is essentially devoid of publications that support the claim that light-weight autonomous machines offer a functional soil compaction management alternative to controlled traffic. Similarly, no papers have been found that investigate the logistical and performance characteristics of small, light-weight machinery options. The issue of light-weight machines as an alternative to controlled traffic has been explored in Chapter 6 (McPhee et al., 2020). As noted in this manuscript, there is no question that light-weight machines will cause less soil compaction than larger machines. That is merely a function of less load on the soil. However, modelling suggests it will be very difficult to achieve acceptable levels of operational efficiency and productivity while reducing soil compaction to the levels that are possible through the isolation of traffic as practiced in controlled traffic. Limitations to the modelling were noted in Chapter 6, and relate specifically to two main issues:

- questions about the ability of current soil compaction models to adequately reflect the behaviour of high clay content soils, and

- options for investigating low ground pressure running gear, such as tracks or IF/VF (Improved Flexion/Very High Flexion) tyres, were not available in the model used.

The impact of these limitations on the findings are addressed in Chapter 6 (McPhee et al., 2020).

The potential of low ground pressure tyres as a means of reducing traffic load impacts on a crop bed managed under seasonal controlled traffic was reported by Vermeulen & Sukkel (2008). This work showed that a load of 2.8 Mg carried on 800 mm section width tyres (the approximate width of a potato row) at an inflation pressure of 40 kPa (below manufacturer's recommendation) did not cause appreciable compaction in the top 0.3 m of the crop beds used in the research, although there would be a large area of tyre footprint. Establishment of a cover crop was significantly higher in the treatment subjected to this traffic load compared to zero traffic. It is likely that this was due to slight firming of the soil by the tyre load, presumably leading to improved seed-soil contact. The loam soil used in the study had not been trafficked in the preceding growing season and was at field capacity at the time of traffic. While this shows it is possible to carry substantial tyre loads on a CTF-managed soil with low risk, the conditions were quite different from those used in the modelling reported in Chapter 6 (McPhee et al., 2020). The compaction status, measured by total porosity, equated to 1.48 Mg m^{-3} (assumed particle density = 2.65), considerably higher than the soil bulk densities of the CTF-managed soils used in the modelling, which were <1.0 Mg m^{-3} for a significant part of the profile, and not more than 1.2 Mg m^{-3} at depth. While Vermeulen & Sukkel (2008) showed improved crop establishment as a result of soil firming, it is proposed that pre-sowing firming of low bulk density soil would be better accomplished with precisely applied and controlled pressure (e.g. a load-controlled roller or press-wheel) than with the random application of loads via vehicle tyres, even if they are light-weight.

The proposal that light-weight robotic machines can be an alternative to controlled traffic focuses on only one aspect – soil compaction minimisation – and ignores a range of other benefits that have been proven to be of significant value in CTF systems. Aspects of CTF that could be compromised by random light-weight traffic include seeding, infiltration and energy use.

In the Australian grain industry, CTF enables inter-row seeding, leading to more efficient operation of seeders, as ground-engaging tools operate between rows of standing stubble, unencumbered by residue. Light-weight machines operating on random traffic patterns, or requiring wide tyres or tracks to reduce compaction, would compromise this benefit. Modelling results reported in Chapter 6 (McPhee et al., 2020) suggest that rut depth could be 50-100 mm in the soil conditions considered. Such rut depths randomly distributed over the field would present challenges for depth control of small seeders. They would also randomly impact overland flow and infiltration and hence soil water content distribution.

Infiltration is influenced by soil bulk density, and therefore soil porosity, and surface conditions, both of which are known to be compromised by wheel tracks. A seven-fold reduction in infiltration rate was observed due to traffic from a small tractor with a rear wheel load of ~0.36 Mg, representing a total tractor weight of ~1.2 Mg, assuming 40:60 front:rear weight distribution (Wang et al., 2008).

Motion resistance represents a loss of useful power in the operation of agricultural machines. Power losses of 2-14% have been reported for tractors operating on soils ranging from zero-till (firm) to ploughed (soft) (Botta et al., 2012). With limited power availability, light-weight machines would benefit from the compacted tracks present under controlled traffic, rather than suffering parasitic energy losses due to motion resistance.

The other critical factor regarding the use of light-weight robotic swarms is their capacity to maintain work rates at least equivalent to fewer, larger machines as currently used. The analysis reported in Chapter 6 (McPhee et al., 2020) concludes that a better option for future development would be the addition of automation (to gain the various benefits associated with autonomy) to medium-sized machines operating in a controlled traffic system. Such an approach could conceivably maintain throughput, provide redundancy through multiple machines and capture all the other benefits associated with controlled traffic.

6.6 A possible future

There remains a significant barrier to overcome in the vegetable industry, and that is the design of controlled traffic compatible machinery. The idea of using automated medium-sized machinery in a controlled traffic system could be implemented in the grain industry with relative ease. The mechanisation basically already exists in the form of smaller tractors and harvesters. The situation in the vegetable industry is very different, in that regardless of size, machinery is still not designed with controlled traffic in mind.

A possible pathway for the vegetable industry combines the automated medium-size approach with the WS, and currently exists in the form of a prototype automated tool carrier (Figure 6-7) (DOT Farming Reimagined, 2019). Designed and manufactured in Saskatchewan, Canada, with the grain industry in mind, the DOT could conceptually provide the basis for a vegetable industry tool carrier. This would still require re-arrangement of many of the implements and components used in current vegetable farming, but in the context of a smaller, automated platform.

Figure 6-8. The DOT autonomous tool frame, which has potential to be used as a small wide span. (Source: DOT Farming Reimagined. https://seedotrun.com)

6.7 Challenges to adoption

Transformational change in agriculture is not easy. The adoptability of change has been shown to be heavily influenced by trialability and reversibility – i.e. the capacity to try something new on a small scale first, and the option to change back if it doesn't work (Kuehne et al., 2017). Regardless of the target industry, controlled traffic usually fails to meet both of these criteria because of the need to either change existing machinery or purchase new machinery in order to achieve the necessary dimensional integration. Once machinery has been changed, by definition the entire system has been changed, thereby failing the small scale trialability test. Change costs money, and to change back costs more money, hence making reversibility difficult. Progress towards adoption then depends heavily on learning about the relative advantages of the system from earlier adopters who are perhaps less concerned about the trialability and reversibility issues, the capacity of potential adopters to learn about the system, its application and its advantages, and the role of influencers in the industry (Kuehne et al., 2017).

Considering the vegetable industry specifically, pathways are apparent for the adoption of various forms of controlled traffic. Adoption of a fully integrated tractor-based system for permanent bed production has been successful in situations where the selection of crops in the rotation suits and the producer concerned had the economy of scale and resources to effect change that required considerable investment over a relatively short period of time. Examples of such changes by Harvest Moon and Mulgowie Farming Company have been noted earlier in this thesis. In the case of seasonal controlled traffic, individual growers are able to make their own decisions about machinery changes for all operations apart from harvest and are hence uninfluenced by the lack of change on the part of harvest contractors. While the adoption of seasonal controlled traffic may involve considerable modification to machinery to achieve compatible track gauge and working width, the transition may not need to occur rapidly, as the soil will continue to be subjected to random traffic until integration of harvest machinery is achieved. The importance of vested interest involvement in the change to permanent bed controlled traffic or seasonal controlled traffic is illustrated by the fact that the examples given earlier in this thesis have occurred at the individual business level for operations over which the business owner has total control.

The question remains as to how to achieve a universal approach to controlled traffic adoption in the vegetable industry, with its diversity of crops and harvest machinery. There are two broad issues to confront, one technical and one institutional.

Commonality of track gauge is the first barrier to address. There appear to be few options other than the wide span to resolve this issue. Whether this is at a large scale, such as the prototype ASA-Lift WS9600, or an adaptation of the DOT Technologies medium-scale autonomous tool frame (DOT Farming Reimagined, 2019), is probably not that important. What is important as a guiding principle is the acceptance of a standard across the industry, and the capacity to adapt a range of readily available or modified implements and technologies to the base machine. This is particularly important in the context of vegetable harvest. With a standard WS platform having a tracked area of

~10% used for all operations, there would be considerable scope to review the spatial arrangements of most crops for the optimum combination of agronomy and mechanisation. As outlined previously, there is nothing particularly new about the WS technology or the range of functions that need to be brought together. What is missing is incentive and influencers.

The Tasmanian vegetable sector is heavily serviced by secondary industry, such as multi-national processors for potatoes and frozen vegetables and local packer/exporters in the case of the fresh sector. In addition, there are post-harvest processors of the pharmaceutical and extractive crops grown in rotation with vegetables. These vertically integrated companies would be key players in any move towards adoption of controlled traffic in the vegetable industry, particularly since they not only control or influence a lot of production through contractual arrangements, but in many cases, they are also the owners of specialised harvesting equipment. Therefore, any change in the production system, and particularly a change as wide ranging as the adoption of WS technology for controlled traffic farming, must include their participation and willingness to support the change. A key requirement is to convince the various industry players of the full range of advantages that could come from controlled traffic adoption, including production, environmental, social and economic benefits and how they apply to all sectors and layers of the industry and the community at large.

In addition to the agricultural production and processing sector, there is also scope for enhanced local manufacturing involvement, thereby expanding the impact of such a change well beyond the agricultural sector. Given the scale of change required to move to such a system, it is also relevant to consider the potential role of government. The benefits of controlled traffic accrue to many sectors of society, from farmers (in terms of improved productivity and resource protection) to the broader community (in terms of reduced environmental impacts from farming and a stronger economy). Therefore, it is entirely reasonable that society, represented by government, has a stake in encouraging such a change to the production system. Government is an active player in many aspects of industry development and operation, and there is no reason why it should not take an active role in facilitating changes of the nature outlined above.

6.8 Summary

There is always more than one possible future for an industry. In terms of mechanisation and soil management in the vegetable industry, one option is to continue on the current path of investing in bigger machines with more advanced technologies to improve efficiency, perhaps with low ground pressure running gear to limit the negative impacts on soil. Given that common soil conditions for irrigated vegetables include high soil water content and high soil disturbance through tillage and some harvest operations (e.g. root and tuber crops), there are significant limits to the effectiveness of low ground pressure options for heavy machinery.

Modelling reported in Chapter 6 (McPhee et al., 2020) suggests that the option of light-weight autonomous machinery is severely constrained by factors such as machine capacity to maintain operational productivity while still being challenged to reduce soil impacts to the equivalent of zero-traffic conditions.

From a systems approach to improved soil management and productivity, the wide span offers many advantages. The concept has been proven over many decades within limited contexts in various industries. While the addition of tillage implements to a wide span tool carrier should be relatively simple, much work remains to be done to integrate a range of harvest technologies into the system. There would be inevitable challenges to such developments, although there is little to suggest such changes are not technically feasible. The biggest single disadvantage of the wide span is that the technology is not currently commercially available, and hence it is difficult to both prove its value as the basis of a farming system and to proceed with the development of a range suitable attachments to undertake the many tasks that would be required in a mixed vegetable production enterprise.

CHAPTER 7. SUMMARY AND CONCLUSIONS

7.1 Summary of thesis

This thesis covers a journey to identify and document some of the challenges, benefits and opportunities of adopting controlled traffic in the mixed vegetable industry, using Tasmania as a case study. Possible pathways forwards are also considered. The findings are no doubt relevant to many other mixed vegetable production systems around the world.

7.1.1 Machinery

There are many possible reasons to explain the low, or in most cases, non-existent adoption of controlled traffic in the vegetable industry. The lack of dimensionally compatible machinery, particularly harvesters, is perhaps the most obvious and challenging to overcome. The mechanisation review reported in Chapter 3 was based on data collated almost a decade ago. Since then, there have been many upgrades of machinery and related technologies in the industry, with the widespread adoption of GNSS guidance being one of the most transformative. However, there has been no fundamental change in the design of harvest machinery, which is the dominant barrier to achieving dimensional integration across the cropping system. Some enterprises have adopted full or seasonal controlled traffic at the individual farm level and within specific crop rotations. This has required modifications to machinery, and in some cases major inventory change. The combination of machinery design and ownership has precluded the development of a universal solution that is applicable to the wider industry. Added to the mix of challenges is that almost all vegetable machinery is manufactured overseas, and Australia, represents a very small portion of the global vegetable machinery market. This does not prevent individual enterprises requesting made-to-order machinery, as evident in the example of Mulgowie Farming Company's bean and sweet corn harvesters outlined in earlier chapters, but this is rare and such opportunities are limited across the diverse range of vegetable harvesters.

7.1.2 Topography

Undulating topography can pose challenges related to soil management, such as erosion and machinery operation, particularly with regard to safety and accuracy of tracking on cross-slopes. The mapping analysis reported in Chapter 3 shows it is theoretically possible to design CTF-compatible layouts in this topography. In the absence of CTF adoption on these slopes, there has so far been no implementation of such layouts to test their functionality. It is plausible that erosion of permanent wheel tracks could be an issue that needs addressing in layouts on steeply undulating land, even though significantly improved infiltration in the non-wheeled zones would be expected to reduce overall surface runoff. The impact of permanent compacted wheel tracks on water and soil movement has not been studied in this environment, although observations from research sites suggest the issue may be less serious than initially imagined.

7.1.3 Soil

Although the research reported in Chapter 4 relates to a farming system that is currently dependent on full soil disturbance, the use of controlled traffic led to beneficial changes in soil physical properties and biology. While the magnitude and rate of change may be less than those found in zero-till situations, the direction of change is consistent with what has been found in other industries and environments, with this work being a relatively rare case of controlled traffic combined with largely conventional tillage operations. Much remains to be done to more fully document the impacts of controlled traffic on a range of soil-water-plant factors (e.g. infiltration, water holding capacity, drainage, structural stability, WUE and NUE, GHG emissions etc.), particularly on different soil types and in the irrigated vegetable production context.

7.1.4 Economics

For all the sustainability benefits that controlled traffic can bring to crop production, the challenges are unlikely to be seriously addressed unless the change can be shown to be economically beneficial. Modelling reported in Chapter 5 indicates the potential positive economic benefits, although there are many uncertainties attached to the assumptions used. As noted in the discussion of Chapter 5, the modelling of CTF in vegetables included scenarios based on two quite speculative assumptions – one that existing harvesters could be modified to dimensionally compatible track gauges and working widths, and the other that WS tool carriers would become a commercially available option. Given that neither of these options appear to be imminently available in the industry, very conservative estimates were used for all inputs to the modelling, with likely returns taken at the lower end of probability, and costs at the higher end. Even so, modelling showed the potential for increases in average net farm return of 60-80% over current conventional practices for three of the four case study farms used. The farm which showed the lowest economic benefits differed somewhat from the others, in that vegetables comprised a smaller component of the rotation, minimum tillage practices had already been implemented, and a transition to seasonal controlled traffic was already in progress at the time of the study.

7.1.5 Opportunities

No doubt there are many more benefits arising from controlled traffic to document in the vegetable production environment. What has been reported in this thesis and other sources indicate positive reasons for adoption. The challenge is how to do it. Chapters 5 and 6 outline one option in the form of the wide-span gantry. Despite its first reported appearance in 1858, significant research into its performance in the latter half of the 20th century, and several attempts at commercialisation in recent decades, the wide span remains a revolutionary approach to cropping mechanisation.

The alternative of drawing on recent advances in automation to limit soil compaction effects through the use of light-weight robotics was explored in Chapter 6. Soil compaction modelling suggests that achieving the soil management goals of controlled traffic and maintaining operational productivity will be very challenging in a light-weight robotics swarm system. This challenge is significant enough in grain cropping. Vegetable production, particularly root and tuber crops, presents another level of challenge altogether. The combination of draught requirements for crop harvest and highly disturbed, low bearing strength soils suggest it is highly unlikely a functional light-weight harvester that does not cause soil compaction could be built.

7.2 Controlled traffic for vegetable production – why and how?

Chapters 4 and 5 outline a number of soil, operational and economic benefits associated with controlled traffic when used in a vegetable production system. Although these papers represent a significant portion of the literature relevant to controlled traffic in vegetable production, they are a small sub-set of the material covered in Chapter 2 (literature review) outlining the many benefits to be gained from controlled traffic across a range of industries. The wide-ranging benefits to be obtained from controlled traffic, and its integration into a farming system, are well reported.

These benefits are potentially transformational for the vegetable industry. The challenge for the industry is how to achieve it, given the diversity of machinery used across a range of crops.

Although soil compaction management is only one aspect of a productive cropping system, it is a key factor in intensive vegetable production and is the underlying foundation of controlled traffic systems. As outlined in Chapter 6 there are three main approaches to managing soil compaction:

1. Minimisation – reduce loads on susceptible soils with the use of low ground pressure running gear.

2. Remediation – use tillage (mechanical or biological) to relieve compaction after damage has occurred.

3. Confinement – use controlled traffic to confine heavy wheel loads to dedicated, compacted wheel tracks.

Confinement has proven to be a very effective approach, although not without its challenges, as has been outlined on a number of occasions in this thesis. There are three potential approaches to adoption of controlled traffic in the vegetable industry, all of which have been covered to varying degrees in the preceding chapters. These are:

1. Fully integrated tractor-based systems for permanent bed production, particularly suited to crops that are not dependent on mechanised harvest or have harvesters that are capable of being specifically designed for the chosen crop spatial arrangement and bed width.

2. Seasonal controlled traffic which can be used when harvest machinery design is not compatible with a fully integrated controlled traffic system. In this system, all operations except harvest are conducted on the same track gauge and from the same tracks, with satellite guidance allowing return to permanent wheel track locations after harvest. The system still offers benefits for the soil, although it is expected that the rate of change would be less than for situations in which full control of all traffic is possible.

3. Adoption of a wide span-based system, either fully across all operations, or as a harvest platform in conjunction with conventional tractors and implements with compatible track gauge and working width.

Of the three options listed above, the first two are achievable within existing mechanisation constraints. While seasonal controlled traffic is an interim measure, the full benefits of controlled traffic won't be captured by the vegetable industry without access to technologies such as WS tractors or some other means of integrating machine dimensions. The WS option requires a transformational change to the way mechanisation is approached in the vegetable industry, although it perhaps does not need to be as difficult as often envisaged since many existing technologies could be adapted to the basic tool frame.

As outlined in Ch 6, the adoptability of controlled traffic is challenged by the criteria of trialability and reversibility. This is particularly the case when success depends on transformational change, as represented by the proposition that the WS provides a universal solution to dimensional integration of machinery across a diverse range of crops in the vegetable industry. Both technical and institutional issues need to be addressed in order to achieve change.

The WS approach, either at a large scale (e.g. prototype ASA-Lift WS9600) or autonomous medium scale (e.g. DOT Technologies tool frame), is a potential solution to the technical challenge of controlled traffic adoption. Acceptance of an industry standard track gauge for a WS would allow adaptation of a range of readily available or modified implements and technologies to fit the base machine, which is particularly important for vegetable harvesting technology. The advantages of such a standard platform, with a tracked area of ~10% across all operations, would provide opportunities to re-imagine the spatial arrangements, agronomic management and mechanisation of most crops in the rotation.

Addressing the institutional issues inevitably involves the post-farm gate sector of the industry. The companies that comprise this sector across the processed and fresh vegetable, and extractive crops, industries are ideally placed to become influencers. Change will not occur without their participation and support. When considering the full range of production, environmental, social and economic benefits that could accrue from controlled traffic adoption using wide span technology, it is also logical that government should be a key facilitator in the process.

7.3 Conclusion

The adoption of controlled traffic as a future pathway presents many challenges, although none that are insurmountable if the motivation is present to improve sustainability and productivity. All of the necessary technologies exist, either in currently used machinery or prototypes. The technical challenge is to bring the various parts together as a system. The other, and potentially bigger, challenge is to generate the industry initiative and cohesion to support the development of a systems approach, with all of the attendant technology to make it work. This is not a metaphorical fork in the road. It literally requires stepping off one path and on to another.

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APPENDIX A. REFERENCES RELATED TO YIELD IMPACTS OF SOIL COMPACTION

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APPENDIX B. REFERENCES RELATED TO CONTROLLED TRAFFIC IN VEGETABLE PRODUCTION

The following list shows 24 references dating back to 1985 that highlight specific research and the relevance of controlled traffic in vegetable production systems, as noted in the Impact Statement of the thesis.

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McPhee, J. E., Antille, D. L., Tullberg, J. N., Doyle, R. B. and Boersma, M. (2020). Managing soil compaction – A choice of low-mass autonomous vehicles or controlled traffic? *Biosystems Engineering,* 195, 227-241. doi: 10.1016/j.biosystemseng.2020.05.006.

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APPENDIX C. PUBLICATION RECORD

Table C-1. Citations of the peer-reviewed papers included in the thesis (total = 52).

Chapter	Authors	Title	Journal reference	Publication year	Citations
3	McPhee, J.E. and Aird, P.	Controlled traffic for vegetable production: Part 1. Machinery challenges and options in a diversified vegetable industry	Biosystems Engineering, 116 (2) pp. 144-154	2013	17
3	McPhee, J.E., Neale, T. and Aird, P.	Controlled traffic for vegetable production: Part 2. Layout considerations in a complex topography	Biosystems Engineering, 116 (2) pp. 171-178	2013	6
4	McPhee, J.E., Aird, P.L., Hardie, M.A., and Corkrey, S.R.	The effect of controlled traffic on soil physical properties and tillage requirements for vegetable production	Soil & Tillage Research, 149, 33-45	2015	18
4	Rodgers, D., McPhee, J., Aird, P. and Corkrey, R.	Soil arthropod responses to controlled traffic in vegetable production	Soil and Tillage Research 180, 154-163	2018	6

5	McPhee, J.E., Maynard, J.R., Aird, P.L., Pedersen, H.H. and Tullberg, J.N.	Economic modelling of controlled traffic for vegetable production	Australian Farm Business Management Journal, 13, 1-17	2016	0
5	McPhee, J. and Pedersen, H.H.	Economic modelling of controlled traffic for vegetable production based on the use of wide span tractors	Australian Farm Business Management Journal, 14, 71-88. ISSN 1449-7875	2017	0
6	Pedersen, H.H., Oudshoorn, F.W., McPhee, J.E. and Chamen, W.C.T.	Wide span – re-mechanising vegetable production	Acta Horticulturae, 2016.1130.83. XXIX IHC - Proc. Int. Symposia on the Physiology of Perennial Fruit Crops and Production Systems and Mechanisation, Precision Horticulture and Robotics, pp. 6551-557. ISSN 0567-7572 (2016)	2016	5

6	McPhee, J. E., Antille, D. L., Tullberg, J. N., Doyle, R. B. and Boersma, M.	Managing soil compaction – A choice of low-mass autonomous vehicles or controlled traffic?	*Biosystems Engineering*, 195, 227-241	2020	0

Web of Science and Scopus citations as of 18 Aug 2020

In addition to the peer-reviewed papers presented in the thesis, the candidate has recently contributed to one additional journal article associated with controlled traffic in general and one book chapter with specific relevance to controlled traffic in vegetable production. A number of local, national and international research and industry conference proceedings related to controlled traffic and associated mechanisation in the vegetable industry have also been produced by the candidate. The conference proceedings span the period during which the project work was conducted and tend to pre-date the publication of the peer-reviewed papers presented in the thesis:

Journal contributions

Bluett, C., Tullberg, J.N., McPhee, J.E. and Antille, D.L., (2019) Soil and Tillage Research: Why still focus on soil compaction?, *Soil and Tillage Research*, 194 Article 104282. ISSN 0167-1987

Book chapters

McPhee, J.E., Pedersen, H.H. and Mitchell, J.P., (2018) Mechanization of Vegetable Production, In G Chen (ed) *Advances in Agricultural Machinery and Technologies*, Taylor & Francis Group, United States, 49-87. ISBN 9781498754125.

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Pedersen, H.H., Sorensen, C.G., Oudshoorn, F.W. and McPhee, J.E. (2013) User requirements for a Wide Span Tractor for Controlled Traffic Farming, International Commission of Agricultural and Biological Engineers, Section V. CIOSTA XXXV Conference "From Effective to Intelligent Agriculture and Forestry", 3-5 July 2013, Billund, Denmark.

McPhee, J.E., Maynard, J., Aird, P. and Tullberg, J. (2013) Economic modelling of controlled traffic in vegetable production, Proceedings of CTF 2013, ACTFA International Controlled Traffic Conference, 25-27 February 2013, Toowoomba, Queensland, Australia.

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