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Reducing Chemical Inputs in Vegetable Production Systems Using Crop Diversification Strategies

By Shane Broad

B. Agric. Sci. (Hons.)

Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

University of Tasmania

School of Agricultural Science and the Tasmanian Institute of Agricultural Research

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Shane Thomas Broad

Abstract

Vegetable cropping systems are becoming larger, more specialised and increasingly reliant on agro-chemicals to manage pests, diseases and weeds. These trends in vegetable production have resulted in increased efficiencies and allowed producers to maintain profitability in a marketplace with greater competition and declining gross margins. However, concern is growing among consumers about the impacts of chemicals on human health and the environment. This research program explores the benefits and costs of alternative vegetable production systems with increased plant species diversity and their potential to reduce chemical inputs.

The first trial conducted in this study focused on strip cropping with the view of adding additional layers of diversity in subsequent experiments. The trial used large plots with mixtures and monocultures of three vegetables: onions (*Allium cepa*), broccoli (*Brassica oleracea* var. italica) and potatoes (*Solanum* tuberosum). These vegetables were chosen to maximise diversity as they all have very different harvested products and do not share any major pests or diseases. This initial trial found that most vegetable diseases were too virulent to control with diversity alone and that onions were very poor competitors and hence not suited to mixed cropping systems. Furthermore, production benefits were found to occur at the zone of interaction, meaning that smaller plots with increased replication could be used in subsequent experiments. There were also trends indicating that the insect pest of broccoli *Plutella xylostella* was restricted by the mixed cropping system.

A cover crop of cereal rye (*Secale cereale*) was chosen as an additional layer of diversity in the second trial conducted in 04/05, due its ability to be easily killed and rolled to form a thick mat of plant material for suppressing weeds. Results from this experiment found that the numbers of *P. xylostella* and the aphid *Brevicoryne brassicae* in broccoli were significantly reduced by the cover crop but not by the broccoli/potato strip crop. Another pest of broccoli, *Pieris rapae*, was not affected by either treatment. The experiments also showed that there were no significant differences in yield or quality of both potatoes or

broccoli, in spite of the fact that broccoli grown in a cover crop matured one week later than broccoli grown in conventionally prepared soil (i.e. a bare soil background).

Experiments in 05/06 showed that reductions in the numbers of *P. xylostella* and *B. brassicae* in broccoli grown in the cover crop were primarily due to interference with host location and not predation or reduced host plant attractiveness. The reductions in *P. xylostella* numbers are of particular significance to Brassica producers as this insect has the proven ability to become resistant to every known insecticide, therefore any non-chemical control method could result in substantial reductions in insecticide use and insecticide resistance. However, *P. rapae* was not affected by the rye cover crop presumably due to superior host location ability and egg spreading behaviour. These results were supported by data from a semi-commercial trial.

In contrast to the previous years results, rye cover crop was shown to have significant effects on broccoli growth, reducing the number of leaves, plant biomass and yield as well as again delaying harvest by approximately one week. However, the rye cover crop improved the quality parameters, reduced the severity of hollow stem, eliminated excessive branching and removed the need for mechanical weeding.

An economic analysis based on the experimental outcomes of this thesis indicated that using the rye cover crop in a broccoli production system reduced the total variable costs by $323/ha (6.7%) but also reduced the gross margin by $151/ha (5.9%) when compared to conventional practice. However, only a 2% increase in yield, or a 7% price premium due to the reduced chemical use, would be required to eliminate this deficit.

The study also showed that mechanical challenges stemming from increasing plant species diversity in existing vegetable cropping systems, could be readily overcome through the modification of existing, commercially available farm machinery/equipment.

In summary, introducing plant species diversity into the conventional vegetable cropping system, in the form of a cover crop, showed considerable benefits to broccoli production in

terms of reduced insect pest pressure and quality improvements. Strip cropping as a diversification strategy did not result in increased yields or quality and had no significant effect on insect behaviour in the crops studied. Furthermore, this approach would be more difficult to implement commercially than the rye cover crop due to increased management complexity and incompatibility of chemical weed management strategies. Therefore future research efforts should focus on increasing plant species diversity in the vertical plane (above and below) using cover crops, rather than the horizontal plane (side by side) using strip cropping.

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Glossary of Terms

Strip crops – growing two or more crops in tractor width repetitions.

Cover crops – plants grown for ground cover that are killed prior to planting a commercial crop.

Bare soil – soil without ground cover that has been cultivated to a fine tilth.

Oviposition – the process of an insect depositing an egg.

DAT – number of days after a seedling has been transplanted.

Host location – the process an insect undertakes when attempting to find a suitable host plant.

Cosmopolitan insect – an insect that is found wherever its host plant is cultivated.

Instar – a post embryonic insect growth stage between moults.

Alatae – winged female aphids.

Apteratae – wingless female aphids.

Degenerate – having lost highly developed functions, characteristics or structures through evolution.

Gravid – carrying developing young or eggs.

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Chapter 1 Introduction

This thesis began as a personal concern rather than an immediate industry based problem. This concern started to develop as I grew up on my parent's mixed crop and livestock property, on the northwest coast of Tasmania, and continued to develop as I worked as a contract vegetable grower before attending University and completing my degree in Agricultural Science. During these years, vegetable production systems increased in scale, and in the process become more reliant on agrochemicals to control competing organisms. My developing apprehension was that agriculture was becoming too reliant on chemicals inputs, which had the potential to increase problems in the future and was perhaps not the best way forward for the industry. These points initiated the question, "Are there any feasible alternatives?" This question forms the starting point of this thesis. However, before beginning to explore this question, the reasons for the current trends in vegetable production systems need to be understood.

1.1 Current trends in modern vegetable production systems

Since the geographical expansion of agriculture slowed markedly in the 1950's, crop yield increases accelerated, more than keeping pace with population growth. This resulted in a worldwide oversupply of food (Swaminathan 2004). Globalisation in agriculture and the continued breakdown of trade barriers enlarged the market available to Australian farmers but also increased the number of competitors (Barr 2004). Both oversupply and globalisation have meant continued downward pressure on agricultural product prices and declining margins between real farm receipts and real farm costs (Laurence 2000). This has led to worldwide structural changes in agriculture over the last four decades characterised by increased mechanisation, intensification of production, increasing use of external inputs and the separation of livestock and crop production (Knickel 1990).

On average, over the last 15 years, agricultural output in the Organisation for Economic Co-operation and Development (OECD) countries has increased by 15%, on 1% less land with 8% fewer workers. At the same time the inflation adjusted price of food has fallen by approximately 1% per annum (Legg and Viatte 2001). To remain globally competitive

Australian farms have become larger, more capital intensive and fewer in number (Garnaut and Lim-Applegate 1998). There has also been increasing pressure to specialise rather than diversify (Stuthman 2002) as specialisation brings economies of scale though greater mechanisation, the use of hybrid germplasm and the focusing of knowledge, research and marketing (Vandermeer *et al.* 1998). Only 50 years ago vegetable producers in Australia were small, diverse, labour intensive operations on the urban fringe with few chemicals and fertilisers available. In comparison, modern vegetable producers are highly productive, large scale, increasingly specialised operations dependent on irrigation, fertiliser, agrochemicals, transport and marketing systems and found in regions where the climate, soil and water supplies are most suited to the production of specific crops (Stirzaker 1999). Access to markets and the relative prices of outputs and inputs strongly influence the selection of crop types, crop sequences and crop management (Boiffin *et al.* 2001).

While these farming systems are extremely productive and provide low-cost food (Altieri 1998; Stirzaker 1999) they also bring a variety of economic, environmental and social problems (Altieri 1998). A focus on maximising production in the short-term without consideration of the consequences on other essential components of the agro-ecosystem has led to natural resource degradation in Australia (Williams and Gascoigne 2003). The annual cost of this resource degradation, which includes salinity, acid soils, soil structural decline, erosion, irrigation salinity, reduced water quality and invasive weed control, has been estimated to be in excess of $A 3.5 billion (Standing Committee on Environment Recreation and Arts 2001).

At the individual farm level there has also been a subsumption of the decision making process by corporations as part of the contracting process (Tonts and Black 2002). For example, in Tasmania, vegetable processing companies make most of the decisions in relation to the selection of varieties, planting and harvesting dates, irrigation schedules, chemical applications and fertiliser requirements, and usually award annual contracts less than a year in advance (Miller 1995). This compounds the imbalance between economic and environmental imperatives, as there is little opportunity for forward planning and attempts to achieve sustainability are afforded low priority (Miller 1995).

There are very few native Australian plants that are grown as crops in any capacity. Instead crops are drawn from a diverse range of geographic locations, from South America to Europe. As a result the remnant ecosystems dispersed throughout the cropping locations have a long evolutionary history distinct from that of the introduced crops (Hill 1993). Therefore most pests, predators and diseases are also exotic in their origin. The insect pest situation is further complicated as many species have the ability to migrate in large numbers on favourable winds, at times inundating biological control mechanisms (Hill 1993).

These factors, combined with modern agriculture's reduced tolerance of weeds, pests and diseases (Vandermeer *et al.* 1998), means maintaining the productivity of soils and sustaining the rural environment in the face of declining farm profitability, is seen as the single most important issue in many agricultural industries today (Laurence 2000). Furthermore, Trewavas (1999) suggests that along with abundant (and cheap) food and greater life expectancies, has come a demand from consumers for a risk free world. Since modern farming practices have been fairly or unfairly associated with chemicals and health risks, there is an increasing demand for 'clean green' chemical free food. There have also been calls for greater use of 'sustainable' production methods in Australia due to continual scrutiny of agricultural production methods by an increasingly urbanised population coupled with an agricultural lobby with waning political power (Barr 2004). These demands are increasingly being reflected in the requirements of retailers, particularly the economically powerful supermarkets in Europe (Gunningham and Sinclair 2002) and Australia.

In summary, the current trends in Australian vegetable production are that increased global supply and competition has resulted in increased farm efficiency, management simplicity, greater reliance on inputs (including agrochemicals) and increased scrutiny by a largely urban public who desire "sustainably" produced goods. Therefore, research into vegetable cropping systems that maintain efficiency and productivity, but at the same time reduce the level of chemical inputs, could result in more marketable products and be an alternative to a

continued reliance on chemical solutions. Researching strategies to reduce chemical dependence in vegetable production also aligns well with current Australian agricultural policy statements, for example Tasmania's state government policy and promotion of Tasmanian agricultural industries as being "clean and green", with low chemical usage, and a moratorium on any use of gene technology in the production of food (Anon 2003b).

1.2 Steps in this research

The search for a feasible alternative to the current trend of increased chemical dependence in vegetable production systems, initially involved discussing the problems of chemical dependence and the benefits and disadvantages of farming systems with reduced chemicals requirements. This led to the initial choice of research direction that was further developed via a review of relevant literature (Chapter 2). This in turn generated specific research questions, with preliminary field investigations commencing in the summer of 2003/2004 with the strip cropping of potatoes (*Solanum tuberosum*), broccoli (*Brassica oleracea* var. *italica*) and onions (*Allium cepa*) (Chapter 3). Initially this project was conceived as a broad look at problems and potential solutions to chemical dependence in each of these three vegetable crops. However, the results from the initial trial demonstrated that the most interesting trends were occurring in broccoli, which is a good example of an intensively produced vegetable with the associated problems of insect pest pressure, insecticide resistance, weed pressure and rapid growth. Therefore the majority of the work in the following two years concentrated on broccoli as a key part of an intensive system. The major focus of this thesis relates to the impact of cover and strip cropping on insect populations in broccoli (Chapter 4). Agronomic and economic impacts are discussed in Chapter 5 and machinery design aspects in Chapter 6. The research detailed in this thesis covers a wide range of subject matter within the field of agricultural science including agronomy, entomology and agricultural engineering. The final chapter, Chapter 7, summarises these different aspects and discusses future research directions.

Chapter 2 Literature review

2.1 The problems of chemical dependence in agricultural production systems

> *"[T]oo often current agricultural production in the industrialized world can be characterized as too many people trying to grow the same crop (perhaps even the same or very similar varieties of that crop) in much the same manner."* (Stuthman 2002)

The initial success of DDT (dichlorodiphenyl-trichlorethane) in the 1930s shifted scientists away from fundamental research on insect biology, physiology and alternate methods of pest control, to developing synthetic organic insecticides for the control of pests. The rapid expansion of insecticide research also resulted in the development of chemicals to control pathogens and weeds. Along with yield gains from the Green Revolution came the economic incentive to chemically protect these yields from pests, pathogens and weed competition (Ruttan 1999).

The economic benefits of chemical protectants, coupled with the economic pressures detailed in the Introduction, has resulted in modern agriculture being characterised by large-scale deployment of genetically uniform seed, tubers or plantlets. This practice has led to both management and genetic simplicity and uniformity on modern farms, and indeed across regions and even countries. Herein lies the foundations of a disease epidemic because if one plant is susceptible to a disease, then vast areas can potentially allow almost limitless expansion of a pathogen (Wolfe 2000). The worst incidences of breakdowns in resistance leading to plant disease epidemics are the 1840's potato famine in Ireland caused by *Phytophtora infestans,* the Bengal rice famine of 1942-1944 caused by *Helminthopsporium oryzae,* and the 1970's Southern Corn Blight epidemic caused by *Fusarium graminearum* (Stuthman 2002). To halt these problems, scientists have developed new chemicals or resistant varieties (Wolfe 2000). However, these practices

place greater selection pressure on pathogens to adapt (Ruttan 1999; Mundt *et al.* 2002) resulting in what is effectively an arms race between scientists and pathogens.

Similar trends are evident in the control of insects as the development of DDT led to a pest control strategy based on total annihilation (Vandermeer 1995) and frequent pesticide applications. This strategy in some instances resulted in resistance, the loss of beneficial insects and increased pest damage. Increasing the number of applications could sustain yields in the short-term but productivity could still collapse (Conway 1987). An example was the cotton industry in the Ord Valley of Western Australia where resistance of *Helicoverpa armigera* to DDT resulted in up to 35 applications of insecticides per season and eventual failure of the industry (Fitt 1994). This situation is not unique to one industry as multiple chemical resistance has also been detected in many other insect species and is increasing despite the introduction of new classes of insecticide (Denholm *et al.* 2002).

The practice of "clean" cultivation means that producers also attempt to eliminate crop competition from weeds and often herbicides are the simplest, most reliable and cheapest method of weed control available (Heap 1997). As a result, growers spend more money on herbicides than any other crop input (Marshall *et al.* 2003). Once again the reliance on chemical management has resulted in resistance problems. Resistant weed species include at least 40 dicotyledonous plants and 17 monocotyledonous plants (Holt *et al.* 1993). While resistance to triazine herbicides are most commonly reported (Holt *et al.* 1993; Heap 1997), at least 60 weed species have biotypes resistant to one or more herbicides from 14 other herbicide classes (Holt *et al.* 1993) and the number of new cases of herbicide resistance has a relatively constant average of nine per year (Heap 1997).

As well as the resistance of insects, pathogens and weeds to chemical controls the increasing reliance on chemicals in modern agricultural production can have other side effects, both real and perceived. Frequent applications of pesticides severely reduce biological diversity destroying a wide array of susceptible species, changing the normal structure and function of the ecosystem (Pimentel *et al.* 1992). Brummer (1998) sums up the current situation:

"Despite millions of dollars of public and private research investment, 50 years of chemical control have only made weeds and pests more difficult to control; though chemicals make management simpler in the short run, they invariably create more extreme problems in the future."

2.2 Possible options for reducing chemical dependence in vegetable production systems

Despite the problems of chemical use illustrated above, the widespread use of chemicals, as part of modern agricultural systems, has bought some distinct benefits including cheap and abundant food. Simply reducing the use of chemicals in agriculture without implementing alternatives could be disastrous, amongst other things, potentially exacerbating vulnerability to crop failure (Clunies-Ross 1995). Some alternatives that could allow a reduction in chemical use have been suggested and these include: (i) the use of transgenic crops, or genetically modified organisms (GMOs); (ii) integrated pest management (IPM); (iii) conversion to "organic" practices; or (iv) applying ecological principles to agricultural systems.

2.2.1 Transgenic crops

In agricultural systems GMOs can be divided into three classes: (i) those producing an insecticidal compound isolated from the bacterium *Bacillus thuringiensis* (Bt); (ii) plants resistant to some form of broad-spectrum herbicide and; (iii) plants with combinations of both.

Bt toxins, when ingested by susceptible insects, are activated by the midgut proteases, which interact with the larval midgut epithelium causing disruption of the membrane integrity and eventual death (Gill *et al.* 1992). In genetically modified Bt plants the Bt genes are inserted into and expressed by the plant. In effect this technology internalises the application of the insecticidal compounds. To prevent the pervasive ability of some insects to develop resistance, a refuge strategy has been widely adopted. This entails planting refuges of non-Bt host plants along with Bt crops to promote survival of susceptible pests. As resistance alleles are often rare and recessive, the susceptible pests will in effect dilute

any resistance that develops, but this in itself does not preclude resistance developing (Tabashnik *et al.* 2003). Since cotton containing a single Bt gene was introduced into Australia to control *Helicoverpa sp*. in 1996, average reductions in pesticide use of over 50% have been reported (Skerritt 2004). Compare this to the previously mentioned use of up to 35 sprays per season before the collapse of the cotton industry in the Ord River region of Western Australia (Fitt 1994).

The use of herbicide resistant plants, whether genetically modified or not, make weed control much simpler but have the potential to facilitate the development of herbicide resistant weeds through genetic transfer to closely related weed species and by creating intense selection pressure for weeds to adapt to the herbicides used. A further problem is seed dormancy, where the herbicide resistant crop germinates as a volunteer weed the following year in the next crop grown in rotation. These concerns and others, along with debate about whether or not herbicide resistant GMOs have improved yields and financial returns to farmers, have led some weed scientists to question whether these GMOs are beneficial (for example Martinez-Ghersa *et al.* [2003]).

There has also been controversy surrounding the development and deployment of genetically modified organisms in agricultural systems in the public arena. For example, widely publicised campaigns by environmental groups like Greenpeace, have called on governments to apply the “precautionary principle” to GMOs where they are banned until the proponent can conclusively prove that the product is safe for the environment and human health (van den Belt 2003). This has led to moratoria on the research and use of GMOs being put in place in some regions, including Tasmania. The Tasmanian State Government’s rationale behind the moratorium on commercial release of agricultural (GMOs) until 2008, was to underpin Tasmania’s reputation for ‘clean, green and quality’ products (Anon 2003a) indicating that from a policy perspective the use of GMOs can also be unpopular.

In spite of the public debate, the use of genetically modified crops can reduce the amount of chemicals directly applied to crops in some agricultural production systems. However,

GMOs do not eliminate chemicals, instead the herbicide use is simplified and/or insecticides are internalised and expressed by the plant instead of being applied to the plant. Therefore GMOs can also be seen as a repackaging of chemical technology not a solution to the dependence on agrochemicals. Furthermore**,** from a practical viewpoint, GMOs cannot be researched for this thesis due to the aforementioned moratorium.

2.2.2 Integrated Pest Management

The concept of integrated pest management (IPM) is becoming more popular with farmers, researchers and policy makers (Thomas 1999) due to concerns over pesticide resistance, human health and environmental impacts (Mo and Baker 2004). IPM seeks to minimise reliance on pesticides by emphasising the use of alternative control methods, including biological control, host plant resistance breeding, cultural techniques (Thomas 1999), and the development of threshold based spray programs in conjunction with time efficient sampling techniques (Mo and Baker 2004). The practice of IPM has received by far the most attention in the quest for "alternative" pest management strategies (Lewis *et al.* 1997).

IPM is complicated and "knowledge intensive" due to the complexity of interactions between plants, pests and natural enemies, which make it difficult to apply pest control prescriptions across all systems (Thomas 1999). This is perhaps why IPM has been adopted in relatively few crops and has yet to significantly reduce the use of pesticides worldwide (Matson *et al.* 1997). In practice IPM has become a monitoring strategy with the establishment of thresholds, and chemicals used on an as needed basis (Lewis *et al.* 1997). Furthermore, corporate planners have embraced IPM because the practice does not eliminate the need for chemicals but rather requires the development of expensive pest-specific or environmentally benign chemicals (Rosset and Altieri 1997). Therefore even with large-scale adoption of IPM, chemical dependence will remain.

2.2.3 Organic production methods

The organic agriculture movement emerged in the 1930's and 1940's as an alternative to an increasingly industrialised agriculture based on nitrogen derived from the Haber-Bosch process (Lotter 2003). That initial movement has developed into a system that attempts to

address concerns some farmers, researchers and consumers have with modern petro-chemical based farming methods (Kondinin-Group 2000).

A working definition of organic agriculture is “good farming practice without using synthetic chemicals” (ATTRA 1995). “Organic” typically denotes an agricultural product grown using practices certified by a recognised organic certification body. In general, proponents of organic production methods claim the practice is better for the environment and human health when compared to conventional practices. Organic producers and consumers also describe organic production methods as being more “natural” and therefore better than “artificial” conventional practices (Verhoog *et al.* 2003). It is essential that these claims are legitimate if organic products are to fulfil the promise that consumers can substantially change agricultural practice for the betterment of the environment (Allen and Kovach 2000). To this end, Treadwell *et al*. (2003) asserts that the ecological and biological mechanisms behind long held and “often ridiculed” beliefs of organic farmers are being elucidated. However, others suggest that the claims of the organic movement are based on “very little science” (Trewavas 2001a) or flawed methodology (for example, claims that organic products are tastier or more nutritious, as discussed by Lotter [2003]).

Other concerns expressed in relation to organic agriculture include:

- The prevalence of input substitution in organic agriculture where organically registered, “natural” products are used instead of an industrially produced pesticides, fungicides or fertilisers, meaning that the system is essentially the same as conventional production (Rosset and Altieri 1997).

- The consequences of wide scale conversion to organic agricultural production on the environment. Compared to conventional production, it is widely reported that across systems organic production methods typically reduce yields by 5% to 60%. Intensive organic systems have the greatest yield reductions when compared to their conventional counterparts, while extensive organic systems have marginally reduced yields compared to conventional systems (Lotter 2003). The outcome of this yield reduction is that if the world were to feed itself using organic farming

principles more agricultural land would be required to produce the same amount of food as conventional production systems, which could lead to the destruction of wilderness areas (Legg and Viatte 2001; Trewavas 2001b).

- The reliance on nutrients from conventional farming systems. Organic farms, especially horticultural operations, rely on wastes from conventional systems in the form of manures, green waste, household wastes and food industry wastes to maintain fertility (Guthman 2000; Watson *et al.* 2002). These nutrient subsidies from conventional agriculture mean that organic agriculture remain indirectly dependent on artificial fertilisers and chemicals. Moreover, if there was wide scale conversion to organic agriculture there might not be adequate supplies of these wastes for all organic producers.

At present organic production remains a set of rules based on a philosophical standpoint and not a proven science in its own right. There is also tension within the organic movement between philosophically committed producers and producers merely operating within the regulations with ideologies more in common with conventional producers (Guthman 2000; Treadwell *et al.* 2003).

In summary, organic systems still use chemicals, albeit chemicals derived from natural sources. These chemicals can still have serious side effects and environmental impacts (Altieri and Rosset 1996). Furthermore, in some instances these more "natural" chemicals can be more toxic than conventional chemicals (for instance "natural" copper sulphate fungicide compared to the conventional equivalent Mancozeb®, as discussed by Trewavas [2004]). In a report of organic farming in Australia by the Kondinin-Group (2000) the majority of concerns about conventional production relate to the use of agrochemicals and their cost. If reduced chemical usage were the dominant reason for consumers to choose organic produce, would it be better to develop "conventional" systems that use fewer chemicals?

2.2.4 Farming systems compatible with ecological principles

Ecological principles suggest that current modern agricultural production systems are relatively unstable and will continue to be prone to invasion by weeds, and high incidences of pests and diseases (Vaughan 1998; Tilman 1999) and thus require constant external inputs to perform (Altieri and Rosset 1996). Many of the major pest problems of today are a direct result of actions taken to improve crop production (Thomas 1999). As a consequence, commentators have been calling for a shift in research effort to blend ecology and agricultural science in order to design stable farming systems based on mimicking species diverse natural systems (Clunies-Ross 1995; Lewis *et al.* 1997; Matson *et al.* 1997; Brummer 1998; Dawson and Fry 1998; Jackson 2002; Rämert 2002).

The recognition that ecological principles can be used in farming is widely accepted as the calls for more research suggest. However, there are both real and perceived problems in applying ecological principles to agricultural production systems. The first is which principles should be used (Wood 1998). Another problem is that the reductionist approach common in science means that simplified systems are easier to study. As Vandermeer *et al.* (1998) states,

> *"..it is possible that a bias is introduced by agricultural research which has an adequate tool-box of experiments and models for technology development in monocultures, but which is less able to deal with more complex systems."*

Furthermore, most soil science and agronomy departments in universities have been "married to agriculture" and have had only fleeting associations with ecology, ecosystem studies or earth sciences (Williams and Gascoigne 2003). Together with the current research paradigm, social pressures, limited funding options, pressure from processors and financial institutions make it increasingly difficult to change from what is perceived as "current practice". As a result there has been little effort to apply ecological theory, models and techniques to agricultural systems (Robertson 2000).

One possible starting point for the application of ecological principles in agricultural systems is the ecological theory of diversity/stability, in which species diverse systems are stable systems that have the ability to resist pest and disease incursions (McCann 2000). An

ecological analysis of modern agricultural systems, as discussed in the Introduction, reveals that genetically homogenous crops do not possess this ecological mechanism to lessen the impact of pests (Altieri and Rosset 1996). If pest and disease outbreaks that require chemical interventions are understood as being the result of an ecological imbalance, then the treatment should be to recover balance or "homeostasis", which is the maintenance of the system's internal functions and defences to compensate for external stresses. The primary technique for achieving homeostasis, self regulation and sustainability is biodiversification (Altieri and Rosset 1996), which in the case of vegetable cropping systems would involve plant species diversification.

The most useful biological standard equivalent of modern vegetable production systems is a rainforest with sustained high levels of primary production, in wet leaching environments through efficient cycling of nutrients and water and stress minimisation through species diversity (Stirzaker 1999). If it is possible to use the rainforest as a biological standard then it is also possible that some lessons can be learned from nature. In particular, the species diversity of rainforest systems hinders the development of pest and disease outbreaks. If the idea of diversity/stability could be successfully introduced into vegetable cropping systems, there is the potential to reduce pest and disease pressure and therefore reduce the need for chemical interventions.

2.3 Research options – the best way forward?

Limiting factors in agriculture represent the symptoms rather than the underlying "disease" inherent in imbalances within the agricultural ecosystem (Altieri and Rosset 1996), therefore a new production paradigm is required. To discover new production paradigms the search has to be very broad (Weiner 2003). Any changes are not necessarily straightforward, as eliminating soluble man-made fertilisers and chemicals completely would reduce vegetable yields, in turn making vegetables more expensive, reducing peoples' intake and increasing cancer rates (Ames and Gold 1997). The movement towards sustainable agriculture is not simple as Legg and Viatte (2001) have discussed:

> *"OECD countries know that agriculture needs to be made more sustainable. But it is not so clear how this can be achieved."*

Applying technological solutions like GMOs or large scale conversion to organic agriculture with its propensity for input substitution, do not address the underlying ecological causes of environmental problems in agriculture, which are rooted in the monoculture structure prevalent in large scale production systems (Altieri and Rosset 1996). IPM aims to change conventional practice and reduce chemical use through monitoring and targeted chemical applications, but is this the best solution to reducing the use of chemicals in agriculture? This practice does not reduce yields if properly implemented and can save costs because chemical interventions are only used when necessary and not on a calendar basis. However, as discussed in Section 2.2.2, IPM in practice has become little more than a monitoring strategy and the use of more expensive selective insecticides.

Using ecological principles shows great promise in reducing chemical use in vegetable cropping systems because experiments have been aimed at treating the underlying causes rather than treating the symptoms with chemicals (like GMOs and IPM), while also being more productive than organic systems. However, as discussed, there are some issues in the use of ecological principles, the most pressing is which ecological principles to use (Wood 1998)? Furthermore, there is a lack of adequate research relating to the integration of ecological principles with farming system design and no clear guidelines to work from. With this in mind, the focus of the research in this thesis is on the introduction of greater diversity/stability in vegetable production systems. The selection of this topic does not detract from the need for, or benefits of the other approaches such as GMOs, IPM and organic principles. Indeed, these alternatives for reducing the use of chemicals in vegetable cropping systems can be incorporated into a species diverse system in the future, potentially further reducing the use of chemicals.

2.4 Introducing plant species diversity into modern cropping systems

Consideration should also be given to problems of farmers discussed in the Introduction, as consumer demands for sustainably produced products go hand in hand with economic

demands for low cost production. Farmers are also business people and their primary goal is to produce food at a profit. Ensuring resource sustainability is not usually their main objective, therefore the integration of ecological theories needs to be focused on enhancing ecological and economic benefits (Robertson 2000). This acts as a further barrier as any change to current cropping systems has to be economically sustainable to be attractive to farmers. As the adage goes, "It's hard to be green when you're in the red." Therefore, research should focus on designing simple cropping systems based on the ecology of simple and productive natural systems (Wood 1998) and not attempting to initially reinvent the wheel. There are examples of simple species-diverse cropping systems in the international literature based on an holistic approach to experimentation. These are building a scientific case for the adoption of diversity in agricultural systems and are typically based on three main options, which include:

- Side by side diversity - planting strips or rows of different crops together (intercropping/strip cropping).
- Vertical diversity - growing a taller crop above an understorey plant (undersowing/cover cropping/living mulches).
- Within crop diversity - planting genetically diverse cultivar mixes (multi-line/species mixtures).

2.4.1 Side by side diversity – intercropping and strip cropping

Intercropping has been defined as the cultivation of two or more crops in such a way that they interact agronomically (Vandermeer 1989). Strip cropping is similar except that the crops are grown in strips wide enough to facilitate separate mechanical management.

Data extracted from 54 experiments by Jolliffe (1997) indicated that, on average, mixtures of different crops were 12% more productive than pure stands. This could be the result of temporal production advantages, which can be achieved when different crops with staggered planting and maturity dates have different resource demands at different times, lessening or limiting competition between crops (Sullivan 2001; Santos *et al.* 2002). Alternating rows of crops can also create edge effects, including greater light interception and wind sheltering, which can lead to higher production levels than individually planted

crops (Clark and Myers 1994; Ayisi *et al.* 1997; Ghaffarzadeh *et al.* 1997; Smith and Carter 1998; Lesoing and Francis 1999). Edge effects can also create greater system resilience and financial risk reduction due to compensatory growth when extra resources (light and nutrients) are available to one crop if another crop performs poorly (Theunissen 1997; Wolfe 2002). Companion effects have also been reported, where the interaction of the different crops can provide cultural benefits like increased nitrogen availability and weed suppression (Hauggaard-Nielsen *et al.* 2001). There is also some evidence that intercropping can reduce insect pest pressure in Brassicas (Bach and Tabashnik 1990; Meena and Lal 2002).

Intercropping and strip cropping both have greater soil and water conservation potential, when compared to conventional practices, due to the effect of variable ground cover reducing surface water flow (Gilley *et al.* 1997) and the wind erosion of soils (Bravo and Silenzi 2002). Using strip cropping also has the added benefit of reducing the intensity of chemical and fertiliser applications, at any one time, on a per paddock basis (Ghaffarzadeh *et al.* 1997). For example, when applying chemicals to one crop in a three-crop strip cropping system, only one third of the cultivated area will be sprayed at any one time and there will be a buffer of two crop strips between spray runs.

The biggest disadvantage with these systems is that they are more complex to implement, manage and harvest than conventional monocultural practices and there is correspondingly a general lack of relevant agronomic information.

2.4.2 Vertical diversity – cover crops and living mulches

Vegetative ground cover in the form of cover crops are a basic component of a sustainable system (Altieri and Rosset 1996). Cover crops and living mulches differ from intercrops in that, although two or more crops are planted together, only one component is harvested while the other is a subsidiary species designed to convey a specific benefit, which could include:

- insect pest control
- erosion control; or

- weed suppression.

There is also a clear distinction between cover crops and living mulches. Cover crops in vegetable cropping systems are typically killed by chemical or mechanical means, prior to planting the harvested component of the system, whereas living mulches remain alive during the course of the growing season.

The most commonly reported benefit of cover crops and living mulches is a reduction in incidence of major insect pests when compared to conventional tillage practices. As a result understorey diversity in cropping systems has been suggested as a method of controlling insect pest pressure (Masiunas 1998) and reducing crop damage (Costello 1994; Theunissen *et al.* 1995; Åsman *et al.* 2001; Hooks and Johnson 2001). However, there is much debate surrounding the actual mechanism of the effect. Some suggest that a reduction in insect pest numbers is due to inhibition/confusion of insect pests (Risch 1981; Andow 1991) (the resource concentration hypothesis). The observed reduction in insect pests might also be due to encouragement of predatory/parasitic insects (Andow 1991; Mensah 1999; Hooks and Johnson 2003) (the enemies hypothesis). A more recent explanation is the "appropriate/inappropriate landing theory" (Finch and Collier 2000). This theory suggests that in diverse environments, like cover crops and living mulches, insect pests cannot effectively discriminate between host plants (appropriate) and non-host (inappropriate) plants which, when compared to simpler, bare soil backgrounds, interferes with oviposition stimulation resulting in fewer eggs and greater emigration.

Like strip cropping and intercropping, cover crops can promote greater soil and water conservation due to the alternating nature of the different crops minimising water flow across the paddock (Gilley *et al.* 1997; Theunissen 1997; Masiunas 1998; Poudel *et al.* 1999; Gilley *et al.* 2002). In addition, Mwaja *et al.* (1996) found over a three-year period that the use of hairy vetch (*Vicia* villosa) and cereal rye (*Secale cereale*) cover crops increased soil organic matter content from 3.07% to 3.48%, whereas conventional cultivation typically reduces the amount of organic matter in the soil (Sparrow *et al.* 1999). Any increase in soil organic matter is beneficial because higher levels contribute to crop

productivity through a positive effect on nutrient concentrations, particularly exchangeable potassium and calcium (Cotching *et al.* 2002).

Cover crops and living mulches can also suppress weeds through competition for resources (Liebman and Dyck 1993; Masiunas 1998). However, this resource competition can result in some negative outcomes such as a reduction in yield in some crops (Mwaja *et al.* 1996; Masiunas 1998). There is also some evidence that vertical plant diversity can reduce the incidence of plant diseases (Theunissen and Schelling 1996) mainly though a reduction in splash dispersal of inoculum (Ristaino *et al.* 1997; Ntahimpera *et al.* 1998). However, like intercropping and strip cropping these cover crops and living mulch systems are more complex than conventional practices.

2.4.3 Within crop diversity – multi-line cultivars and cultivar mixtures

Charles Darwin observed as far back as the 1870's that variety mixtures of wheat yielded more than single varieties (Wolfe 2000). Only later did it emerge that mixtures restrict the spread of pathogens by providing a physical barrier to the dispersal of spores, due to differential disease susceptibility within the mixture (Wolfe 2000); resulting in less disease transfer in the system (Garrett and Mundt 1999; Wolfe 2000; Garrett *et al.* 2001; Wolfe 2002); compensatory growth and yield by one component when another component is diseased (Garrett and Mundt 1999); and decreased pathogen virulence (Zhu *et al.* 2000). There is the possibility that contact with a pathogen to which a plant has some genetic resistance, could lead to an activation of protection mechanisms and immunisation from a pathogen to which the plant has no genetic protection (Wolfe 2000).

These factors have led to the development of multi-line cultivars and cultivar mixtures as a plant protection mechanism. These two strategies are very similar, the only difference is in the breeding for phenotypic uniformity, in that multi-lines have been subjected to additional breeding for phenotypic uniformity of agronomic traits, while cultivar mixtures have not (Mundt 2002). Notable examples of within crop diversity include investigations of simple mixtures of rice varieties (*Oryza sativa*) to restrict the development of rice blast (*Magnaporthe grisea*) in the Yunnan Province of China (Zhu *et al.* 2000), and the reduction in the use of fungicides in barley (*Hordeum vulgare*) mixtures in the former East Germany

(Wolfe 1992). Cultivar mixtures and multi-lines are also methods of increasing the durability of the resistance. They achieve this by non-selectively suppressing an entire pathogen population to below the economic disease threshold rather than attempting to totally eliminate a pathogen, which is the primary cause of pathogens overcoming resistance genes (Stuthman 2002).

Although genotype and species mixtures are well known in traditional agricultural systems, there is less awareness of the increasing use of genotype mixtures in commercial agriculture (Wolfe and Finckh 1997; Garrett and Mundt 1999 and references therein). There are also problems with government policies and plant breeders' rights making the sale of multi-lines and cultivar mixtures more difficult (Wolfe 1985).

2.4.4 Other levels of diversity

Trap crops, or plant stands grown to attract insects or other organisms away from commercial crops, have the potential protect target crops from pest attack. However, while suggestions for "potential" applications are abundant there have been few successful examples of the practical application of trap cropping systems (Hokkanen 1991). Although modelling of insect herbivore movement and colonisation by Banks and Ekbom (1999) showed that trap cropping had, "great potential in the design of pest control strategies", the modelling work is yet to be validated by field experiments.

The levels of diversity discussed in this thesis operate at the paddock scale. Diversity at larger scales, for example the field margin, landscape or region level (Baudry and Papy 2001; Giulio *et al.* 2001; Coeur *et al.* 2002; Marshall 2002; Marshall and Moonen 2002) is outside the scope of this study.

2.5 Conclusions and research starting point

This literature review has identified that the application of the ecological principle of diversity/stability to vegetable cropping systems has the potential to reduce the use of agrochemicals. While GMOs, IPM and input substituting organic systems to a large extent can reduce the use of agrochemicals in vegetable production systems, they tend to treat the

symptoms, whereas the application of ecological principles to vegetable cropping systems has the potential to treat the underlying causes. Research in this area is needed to address gaps in the current knowledge and to inform the development of clear guidelines. In choosing this line of enquiry GMOs, IPM and possibly organic farming methods have not been discarded, as there is the potential to develop synergies with species diverse systems in the future to create greater system stability/sustainability.

The three main options for increasing plant species diversity in vegetable cropping systems, as discussed were: side by side diversity (intercropping/strip cropping); vertical diversity (cover cropping/living mulches); or within crop diversity (species mixtures/multi-lines). All these strategies require more complicated management than conventional practices. While the design of machinery capable of harvesting two crops simultaneously is feasible (Vandermeer 1989), the simplest diversification strategy to mechanically manage would be strip cropping because each crop could still be planted and harvested with existing equipment without modifications. From a management perspective, the only difference between strip cropping and conventional practice is that there are two or more crops growing in alternating tractor/harvester/planter width replications of each crop that facilitate separate management (the tractor width being the minimum replication that still allows separate mechanical management in the following experiments). This practice also aligns well with the previously stated goals of maintaining the production system's efficiency and simplicity. Therefore the rational starting point for the preliminary investigations (Chapter 3) involved strip cropping as the initial diversification strategy, with the view of increasing the systems complexity in following experiments and answering the following broad research questions:

1. Does increased plant species diversity decrease/increase insect pest, disease and/or weed pressure and could this lead to less dependence on chemical inputs in vegetable cropping systems?
2. What are the practical management and economic implications of increasing plant species diversity in vegetable cropping systems?

The question of vertical diversity, specifically cover crops, will be examined in later chapters.

Chapter 3 Preliminary investigations

3.1 Introduction

This chapter reports on the preliminary trial conducted in the summer of 2003/2004 to investigate the disease, pest, yield, quality and management implications of a vegetable strip cropping system, which included the choice of the crops and the experimental design. The trial provided valuable insights into the system under investigation and strongly influenced the direction of subsequent trials in the following two seasons.

3.2 Methodology

3.2.1 System design

The initial trial design was loosely based on 5m wide replications of a three crop strip farming system developed in North America, typically comprised of maize, soybeans and a cereal grain (Ghaffarzadeh *et al.* 1997; Gilley *et al.* 1997; Lesoing and Francis 1999). The main rationale behind selecting three crop components for the experiment and not more was to limit the number of possible two-way interactions, which become more numerous as the number of crops increases, as Table 3.1 indicates. Extrapolation of these data to four crops or more would result in an unmanageable experiment.

Table 3.1. Interactions in a model crop system, in a one, two or three crop system, adapted from Parkhurst and Francis (1986).

Crop/s	Genetic factors	Cultural factors	Climate-soil	Total factors	Possible two-way interactions
Crop **M**=Maize	1. Crop genotype **M** 2. Pest genotype **M** 3. Crop **M** x pest **M**	1. Land Prep. 2. Cultural practices 3. Fertilisation 4. Pest Control	1. Light 2. Rainfall 3. Soil type 4. Wind 5. Topography 6. Rainfall distribution 7. CO_2	**15**	**105**
Crop **M** = Maize Crop **B** = Bean	1. As above – Plus… 2. Crop genotype **B** 3. Genotype **M** x Genotype **B** 4. Pest **B** 5. Pest **M** x Pest **B** 6. **M** and **B** x Pests	1. As above – Plus… 2. Separate plantings 3. Relative planting dates 4. Density **M** 5. Density **B** 6. Spatial arrangements 7. Harvest	As above	**26**	**325**

Crop/s	Genetic factors	Cultural factors	Climate-soil	Total factors	Possible two-way interactions
Crop **M** = Maize Crop **B** = Bean Crop ***P*** = Potato	1. All of the above - Plus… 2. Crop Genotype ***P*** 3. Crop **M** x Crop ***P*** 4. Crop **B** x Crop **M** 5. Pest Genotypes **M** 6. Pests **M** x Pests ***P*** 7. Pests **B** x Pests ***P*** 8. Crop **M** x Crop **B** x Crop ***P*** x Pests	1. All of the above – Plus… 2. Separate planting dates of ***P*** 3. Relative planting rates 4. Densities of ***P*** and others 5. Spatial organisation of ***P*** 6. Cultivation of three crop system 7. Complications in harvest	As above	**39**	**741**

3.2.2 Crop selection

The crops that were chosen for the initial investigations were potatoes (*Solanum tuberosum*), broccoli (*Brassica oleracea* var. *italica*) and onions (*Allium cepa*). These crops were chosen on the basis of economic importance and their compatibility from agronomic and pest suppression perspectives. As Table 3.2 indicates, there are major differences between these crops in terms of their family, genus, method of propagation, planting date and harvested product. Additionally, under typical Australian conditions they do not share any major pests or diseases, limiting the potential for cross infection and the potential for insect pest outbreaks to affect different system components. There is also evidence that broccoli and potato plants, when grown in combination, have complementary canopy structures and demonstrate temporal asynchronies of growth rates, which can reduce competition for resources, compared to single stands of each crop, potentially facilitating higher yields (Santos *et al.* 2002). Traditional companion planting literature also indicates that broccoli, potatoes and onions are “compatible” (Kuepper and Dodson 2001).

Table 3.2. Differences in onions, potatoes and broccoli under typical Australian conditions, complied from Dueter (1995); Kirkman (1995); Salvestrin (1995); Dennis (1997); Donald *et al.* (2000); Horn *et al.* (2002).

	Onions	**Potatoes**	**Broccoli**
Planting date	Early Spring	Middle to late Spring	Year round
Genus	Allium	Solanum	Brassica
Propagation	Seed	Tuber set	Plantlet (speedling)
Harvest date	Early Autumn	Autumn	Year round
Harvested product	Bulb	Tuber	Immature inflorescence
Major insect pests	Thrips (*Thrips tabaci*)	Potato moth (*Phthorimaea operculella*)	Diamondback moth (*Plutella xylostella*), Cabbage aphid (*Brevicoryne brassicae*)
Minor insect pests	Cutworm (*Agrotis spp.*), Red-legged earth mite (*Halotydeus destructor*)	Green Peach Aphid (*Myzus persicae*), Potato Aphid (*Macrosiphon euphoriae*)	Cabbage white butterfly (*Pieris rapae*), Green peach aphid (*Myzus persicae*)
Major diseases	Onion white rot (*Sclerotium cepivorum*), Downy mildew (*Personospora destructor*)	Late blight (*Phytopthora infestans*), Seed piece decay (*Erwinia* spp., *Fusarium* spp.), Common scab (*Streptomyces scabies*), Powdery scab (*Spongospora subterranea*), Black scurf (*Rhizoctonia solani*), Silver scurf (*Helminthosporium solani*), Bacterial wilt (*Pseudomonas solanacearum*), Leaf roll virus	Club root (*Plasmodiophora brassicae*), White blister rust (*Albugo candida*)

	Onions	Potatoes	Broccoli
Minor diseases and post harvest diseases	*Fusarium* spp., *Botrytis* spp., black mould (*Aspergillus niger*), *Penicillium* spp., soft rots (*Pseudomonas* spp., *Erwinia* spp.)	Target spot (*Alternaria solani*), black leg (*Erwinia carotovora*), soft rot (*Erwinia* spp.), dry rot (*Fusarium* spp.), tomato spotted wilt virus, nematodes	Downy mildew (*Peronospora parasitica*), black leg (*Leptosphaeria maculans*), black rot (*Xanthomonas campestris* pv. *campestris*), head rot (*Pseudomonas* spp., *Erwinia* spp.)

Potatoes, broccoli and onions are also significant agricultural commodities in Australia in terms of the area planted, tonnage produced and associated crop value (Table 3.3). This was deemed to be an important consideration as any long-term strategy for the adoption of strip cropping by vegetable growers would rely on demonstrating beneficial effects in crops of commercial significance, rather than niche, unknown or unmarketable products.

Potatoes are the fourth most important crop in the world after wheat, rice and corn (Kirkman 1995) and in terms of area, volume and dollar value are by far the most significant vegetable product grown in Australia (Table 3.3). Processing potatoes are an important component of the potato industry with an annual production of 460,000 tonnes, worth approximately AU$ 95 million. Two Tasmanian potato factories based at Ulverstone (Simplot) and Smithton (McCains), produce virtually all of the French Fries and associated products for the Australian market (Anon 2003c).

Broccoli is typically established through transplants and is a fast growing crop that matures in approximately 9-10 weeks over summer and is harvested as an immature inflorescence (head). Hence, when compared to other potential crop choices established from seed, broccoli reduces the period of inter-plant competition allowing slower growing neighbouring crops additional access to resources.

Table 3.3. Australian vegetable production for 2003 (ABS 2003)

Vegetable	Area planted (Hectares)	Area ranking (Hectares)	Volume of product (Tonnes)	Volume ranking	$Value of production ($M)	Value ranking
Asparagus	2286	13	12223	14	58.4	12
Beans	6951	6	34626	12	60.5	10
Broccoli	**7285**	**4**	**55083**	**9**	**81.8**	**8**
Capsicums, Chillies and Peppers	2485	12	40810	10	72.1	9
Carrots	7367	2	305699	3	161.8	4
Cauliflower	3879	11	72973	8	58.8	11
Green Peas	5527	9	27837	13	13.9	14
Lettuce	6134	8	121508	6	105.6	7
Melons	6970	5	175105	5	113.7	6
Mushrooms	128	14	39288	11	192.7	3
Onions	**5263**	**10**	**228608**	**4**	**126.1**	**5**
Potatoes	**35899**	**1**	**1247268**	**1**	**484.9**	**1**
Pumpkins	6584	7	93116	7	48.9	13
Tomatoes	7309	3	364368	2	225.5	2
Total	**104067**		**2818512**		**1804.7**	

Brassica crops, including broccoli, have been widely studied as a component of alternative cropping strategies (for example Santos *et al.* [2002]) and non-chemical pest management strategies (for example, Costello [1994]; Hooks and Johnson [2003]). There is evidence that chemical control measures in broccoli are losing their effectiveness, with the detection in South Australia of multiple insecticide resistance in diamondback moths (*Plutella xylostella*) (Baker and Kovaliski 1999), the major insect pest of broccoli (Talekar and Shelton 1993). In Hawaii, this insect has developed resistance to new insecticides with novel modes of action (Zhao *et al.* 2002), suggesting that the development of non-chemical insect pest management strategies should be a priority.

A potential benefit from the inclusion of onions in a strip cropping system are volatiles produced by the crop, which have the potential to inhibit herbivorous insects and benefit other strip cropping system components (Uvah and Coaker 1984). Onion exports from

Australia have suffered in recent years due to the incidence of fungal diseases such as *Botrytis* spp., which have reduced storage life and quality. Consequently, improvements in disease management could result in significant gains to the vegetable industry.

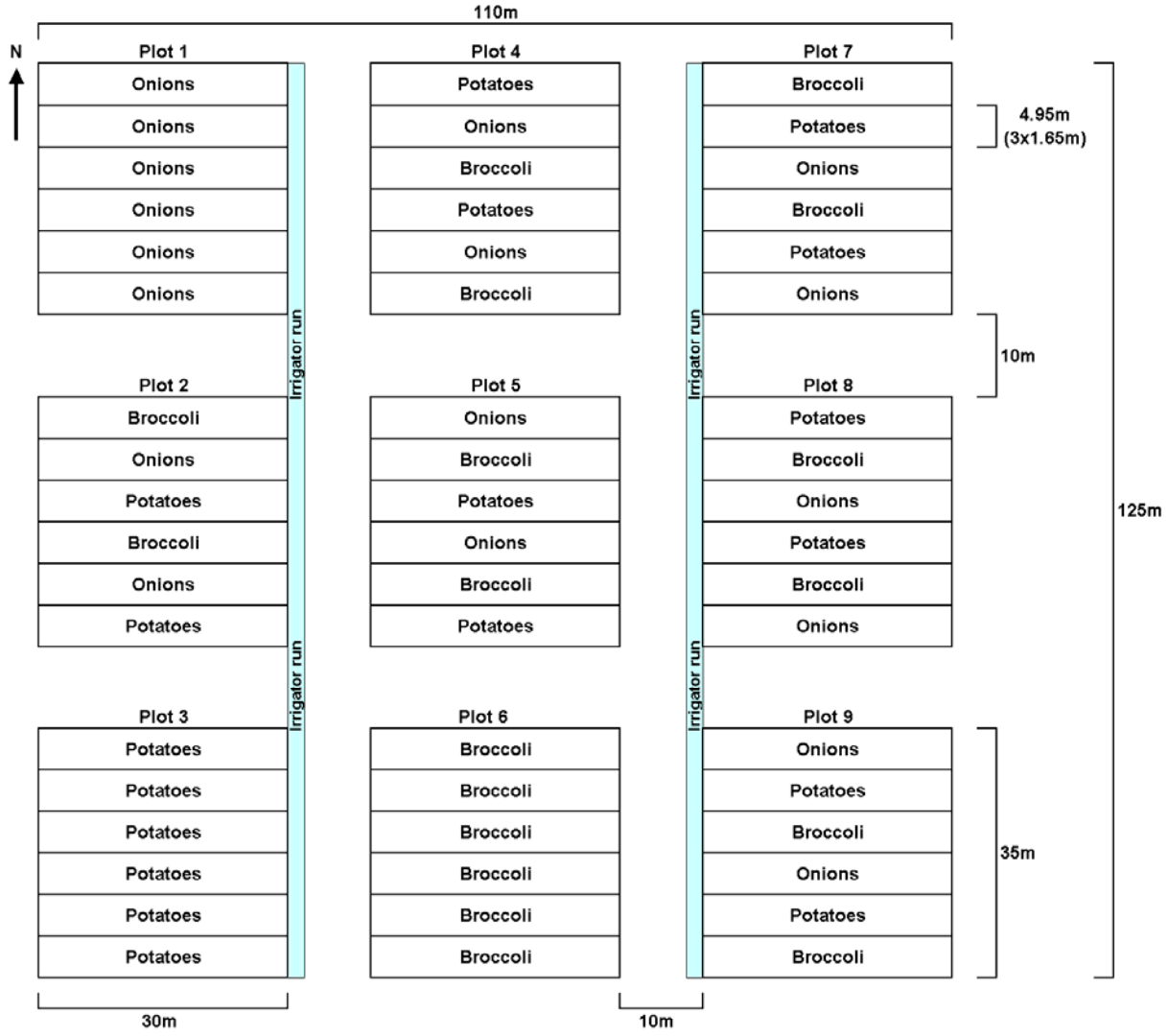
3.2.3 Experimental design

The scale of this experiment was influenced by two factors: the broad ranging research objectives outlined in the Literature Review; and the possibility that interactions between plants, pests and diseases could operate at different spatial scales. In ecological studies there are often scale dependent tradeoffs meaning that large plots are often required to reduce small plot interference (errors resulting from the extrapolation of data from small plots to larger scales), which in epidemiological experiments can sometimes completely mask the effects of diversity on disease progression (Mundt *et al.* 2002). As suggested by Bommarco and Banks (2003), when conducting vegetation diversity experiments, "…large scale questions should preferentially be asked at large spatial scales, after which the underlying mechanisms of observed patterns can be tested at smaller spatial scales." However, following this recommendation reduces the opportunity to replicate treatments in blocks. A further complication in the choice of trial design was the requirement that all plots had to be large enough to be managed using tractor-operated machinery to demonstrate that any findings could be readily applied to real-life farming systems. These factors led to a completely randomised design being chosen with a high degree of internal replication (strips within plots) rather than external replication (blocking). While a completely randomised design has less statistical precision than other designs (Petersen 1994) it offered a number of benefits including flexibility and simplicity of analysis, meaning that the number of treatments and replications per treatment need not be the same. A similar design had also been used before in a habitat diversification experiment without replication (Samu 2003).

Nine 30x30m ($900m^2$) plots were used with 10m buffers in between and approximately 1.65m of bare soil surrounding each plot. The total area of the experiment was approximately 1.2 hectares. Three plots were "monocultures" of each of the three focus crops. The remaining six plots had two sub plot repetitions of three 4.95m wide strips of

each crop comprised of three replications of 1.65m tractor wheel centres. These strips were planted using all possible combinations of the three crops (Figure 3.1).

Figure 3.1. Experimental design for 03/04.



3.2.4 Trial establishment

The trial was established at the Forthside Vegetable Research Station on Tasmania's northwest coast (E 438105, N 5438253) in August 2003. The soil at Forthside is a dark reddish brown, well-drained, heavy clay loam ferrosol (Krasnozem). After ploughing the trial area, the buffer areas between plots were sown with ryegrass (*Lolium perenne*) while the areas to be cropped were left fallow for approximately two months. A bed width of

1.65m was used to match the 1.65m wheel centres of the tractors and other equipment at the research farm. On 10 September 2003, each plot was marked out with white pegs placed in the middle of the first bed at both ends of each crop strip (the first of three beds) for the tractor operator to line up with in order to keep the beds straight. To maintain simplicity each crop type was managed separately using conventional district practices.

Due to the large scale of the experiment, irrigation was applied using a travelling irrigator, which is also standard industry practice for the region. Again to maintain management simplicity, irrigation scheduling was based on Class A Pan derived water use estimates and not individual crop requirements. To improve application uniformity the irrigator was set up to perform two runs over the experimental area, the first run was in a line along the edge of Plots 7, 8 and 9, and the second run was in a line along the edge of Plots 1, 2 and 3 .

3.2.5 Monitoring of crops for pests and diseases

Each crop was monitored for pests and diseases on a regular basis. Commercial practice typically involves the use of chemical disease protectants and insect management strategies, which aim to maintain diseases and insect pests at negligible levels. However, for the purposes of this experiment, higher than commercial pest and disease thresholds were adopted in order to determine if the strip cropping plots were more or less robust than single species plantings.

3.2.6 Onion management and data collection

Onions (*Allium cepa* L. cv. Cream Gold) were planted on 30 September 2003, with 13:14:13 NPK fertiliser at the rate of 650kg/ha, in eight rows per bed with a target density of approximately 60-80 plants/m^2 in line with industry practice (Boersma M., Agronomist, Field Fresh Pty Ltd, *pers. comm.* 2003)(Picture 3.1).

Picture 3.1. Onions planted into three beds per strip with 8 rows of onions per bed.

Weeds were controlled with herbicides according to standard commercial practice, using a modified sprayer with a five-metre boom, which equates to three tractor widths (the design and use of this sprayer is discussed in Chapter 6). The chemical applications were: 26 November Tramat® (ethofumesate 1 kg a.i./ha); 4 December Tribunil® (methabenzthiazuron 1.05kg a.i./ha) and Totril® (ioxynil 0.375kg a.i./ha); 9 December Tribunil® (methabenzthiazuron 1.05kg a.i./ha) and Totril® (ioxynil 0.375kg a.i./ha). The onions were lifted on the 4 April 2004 in order for the bulbs and blades to dry and the skins to harden before harvest on 20 April 2004 (Picture 3.2).

Picture 3.2. Onions after lifting.

Each bed (tractor width) was randomly sampled using a 0.5m^2 quadrat. Two quadrats were taken for each bag and there were three bags to each bed (3m^2)(Picture 3.3 and Picture3.4).

Picture 3.3. Onion yield sampling using a 0.5m^2 quadrat.

Picture 3.4. Onions bagged for yield sampling, Plot 4 (left) and Plot 1 Onion monoculture (right).

These bags were then weighed and the three bags from each bed were sorted into five size (diameter) categories: less than 40mm, 40-50mm, 50-60mm, 60-70mm and greater than 70mm (Picture 3.5 and Picture 3.6). These categories were labelled 40, 50, 60, 70, and 70+ respectively. Each category was then weighed separately.

Picture 3.5. Onion size scale (left to right) >70mm, 60-70mm, 50-60mm, 40-50mm and <40mm.

Picture 3.6. Onion grading equipment.

After the yield sample was taken the remaining onions were removed using a commercial harvester and were not analysed (Picture 3.7).

Picture 3.7. Onion harvester (left) and close up of the harvester's lifter (right).

3.2.7 Potato management and data collection

Potato sets (cv. Russet Burbank) were planted using a twin row cup planter on 6 November 2003 with 1710kg/ha of 11:13:19 NPK fertiliser (Picture 3.8). Two Technical Officers on the planter ensured there was a potato set each in position (Picture 3.9). The intra-row potato set spacings were 320mm and there were two potato rows per tractor width.

Weeds were controlled on one occasion at 20% potato emergence (26 November) with Sprayseed® (paraquat 0.189kg a.i./ha and diquat 0.161kg ai/ha) and Sencor® (metribuzin a.i. 0.097g/ha) using the modified 5m sprayer. Disease levels were assessed visually and samples of diseased plants and tubers collected on 5 February 04 were analysed at the Department of Primary Industries, Water and Environment's Diagnostic Services to determine which diseases were present.

Picture 3.8. Front view (left) and rear view (right) of the potato planter.

Picture 3.9. Technical Officer assuring potato set regularity.

The harvest sample was taken by digging three randomly allocated 1m long sections of each row with a potato fork (Picture 3.10 and Picture 3.11). Rotten tubers encountered were tallied and then discarded and the remaining tubers were collected in a labelled potato sack.

Picture 3.10. Potato yield sample being marked (left) and dug with a potato fork (right).

Picture 3.11. Technical officer taking potato yield samples.

The samples were weighed and then graded, using commercial specifications into different size ranges (850g-250g; 250g-75g; and 75g and less). The tubers were then washed and any tubers with defects were removed and weighed. The potatoes remaining in the field were harvested using a commercial harvester and not analysed.

3.2.8 Broccoli management and data collection

Broccoli Speedlings (*Brassica oleracea* var. *italica* cv. Green Belt) were transplanted on 11 November 2003 with 500kg/ha of 14:14:12 NPK fertiliser including 1% boron, using a 6-row transplanter (Picture 3.12). The Speedlings were transplanted in two rows per 1.65m bed in a 300mm x 800mm grid, with 300mm between plants and 800mm between rows.

Picture 3.12. Six row broccoli transplanter, rear view (left) front view (right).

Using the 6-row planter meant that one entire strip (three 1.65m beds) could be planted in one pass. The monoculture plot (Plot 6) was planted first in order to ensure that any planting problems were resolved before broccoli was transplanted in the strip cropping plots between onions and potatoes.

The broccoli was weeded on three occasions; using a push weeder (Picture 3.13) on 3 December, hand hoeing between plants on 10 December, and finally using a tractor mounted cultivator on 15 December 2003.

Picture 3.13. The push weeder.

The plants were monitored for the presence of disease and insects approximately once a week until the final harvest was completed. An insect sample taken on 8 December indicated that the broccoli was carrying large numbers of diamondback moth (*Plutella xylostella*) (Lepidoptera: Plutellidae). To restrict insect damage and maintain marketability, while at the same time minimising harm to beneficial insects, the broccoli plants were sprayed with Entrust (spinosad 0.128kg ai/ha) on 9 December and again on 16 December.

The first broccoli harvest cut was completed on 9 January 2004, and subsequent cuts were completed on 13, 16 and 21 January. Harvesting of the broccoli heads was performed manually using a knife (Picture 3.14.a). Harvest personnel were given instructions on minimum commercial head size and stem length requirements and then monitored to ensure that the stated standards were consistently maintained. As each cutter harvested two rows at a time, care was taken to ensure that broccoli from each row was placed in the appropriate bag (Picture 3.14.b).

Picture 3.14. (a). Manual harvesting (cutting) of broccoli (left). (b). Harvesting broccoli into bags hung by nails on the inside of two half tonne bins (right).


Each bag was then weighed, with the same Technical Officer weighing the bags for the duration of the analysis (all four cuts) to ensure consistency. The bags were then emptied onto a large table and the broccoli was separated into three categories: significantly affected by white blister rust (*Albugo candida*), odd shape broccoli and marketable broccoli. To remain consistent, instructions were given on the level of infection that constituted significant damage (Picture 3.15), and then the same Technical Officer determined the incidence for the entire analysis (all four occasions).

Picture 3.15. Scale of infection of harvested broccoli heads with white blister rust (*Albugo candida*) progressing from a no infection (left) to a high infection (right) likely to lead to rejection at the factory.

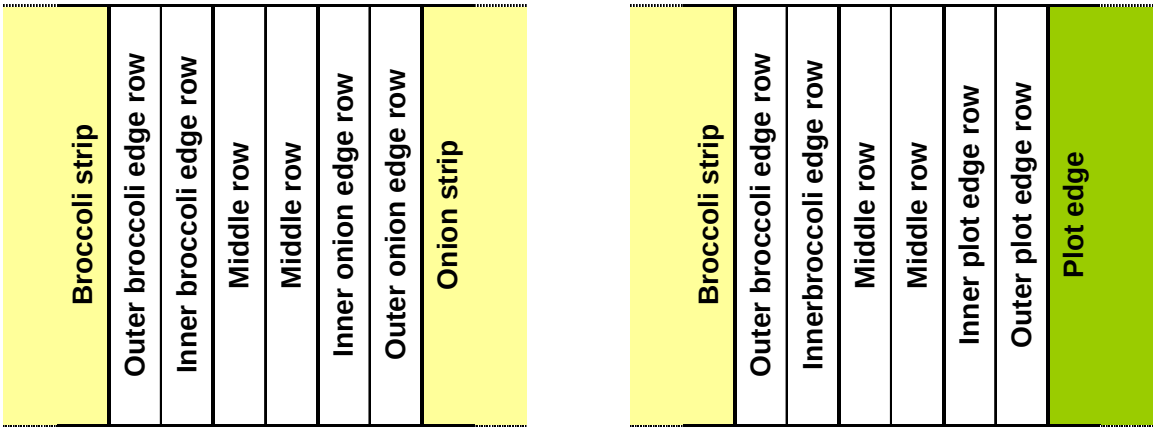
Counts were then made of the total number of heads in each category and the combined total.

3.2.9 Data analysis

The data were analysed with a one-way analysis of variance (ANOVA) using the general linear model (Proc GLM) of SAS v8.2 (SAS Institute, Cary, NC). The various mean counts from each crop row were used as the response variables, while the plot and the neighbouring plant row were the predictor variables. A sample analysis is presented as an appendix. Statistically significant treatment means ($P < 0.05$) were separated using Fisher's least significant difference (LSD). Data were log +1 transformed when necessary to conform to the assumptions of the ANOVA procedure. Data expressed as proportions were first arcsine square root transformed before analysis. However, only non-transformed means were reported, except where otherwise noted.

To determine the treatment effects of strip cropping, pairwise contrasts were planned. These contrasts compared the results from the monoculture plots with the results from rows of plants grown immediately adjacent to rows of other crop types, the plants growing immediately adjacent to the plot edges and the rows in the middle of the strip cropping plots. In the case of potatoes and broccoli the six row strips were broken up in the following manner: left and right outer edge rows, left and right inner edge row, two middle rows, inner edge row and outer edge row. Schematic representations of the naming of rows within a potato strip in the middle of a plot and on the edge of a plot are presented in Figure 3.2. A similar naming protocol was applied to the equivalent broccoli rows.

Figure 3.2. Schematic of naming of a middle 4.95m potato strip cropping strip (left) and a schematic of a 4.95m potato strip cropping strip on a plot edge (right).



The following pairwise contrasts were planned for the potato results:

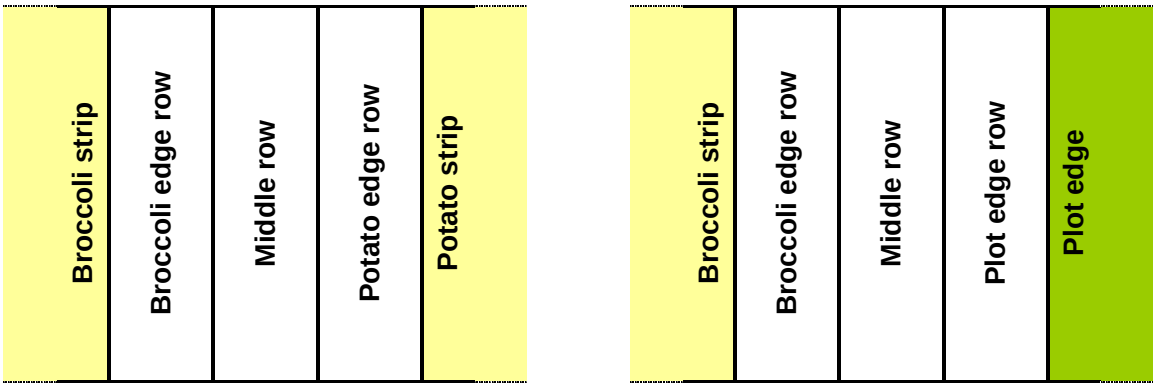
1. Both inner and outer broccoli edge rows vs. Potato monoculture
2. Outer broccoli edge rows vs. Potato monoculture
3. Both outer and inner onion edge rows vs. Potato monoculture
4. Outer onion edge rows vs. Potato monoculture
5. Both outer and inner plot edge rows vs. Potato monoculture
6. Outer plot edge rows vs. Potato monoculture
7. Both middle strip cropping rows vs. Potato monoculture
8. All strip cropped potato rows vs. Potato monoculture

The following contrasts were planned for the broccoli results:

1. Both inner and outer potato edge rows vs. Broccoli monoculture
2. Outer potato edge rows vs. Broccoli monoculture
3. Both inner and outer onion edge rows vs. Broccoli monoculture
4. Outer onion edge rows vs. Broccoli monoculture
5. Both inner and outer plot edge rows vs. Broccoli monoculture
6. Outer plot edge rows vs. Broccoli monoculture
7. Both middle strip cropping rows vs. Broccoli monoculture
8. All strip cropped broccoli rows vs. Broccoli monoculture

An inability to separate individual onion rows due to the mechanical lifting of each onion bed to allow *in situ* drying and maturation of the bulbs, restricted the analysis of the onion results to the 1.65m bed level. This resulted in a reduction in the number of possible pairwise contrasts and the breakdown of the strips into outer edge row, middle rows and outer edge row. A schematic of this naming process is represented in Figure 3.3.

Figure 3.3. Schematic of naming of a middle 4.95m onion strip cropping strip (left) and a schematic of a 4.95m onion strip cropping strip on a plot edge (right).



Therefore the following contrasts were planned:

1. Broccoli edge rows vs. Onion monoculture
2. Potato edge rows vs. Onion monoculture
3. Plot edge rows vs. Onion monoculture
4. Middle strip cropping rows vs. Onion monoculture

Example ANOVA tables are presented as appendices.

3.3 Results

3.3.1 Meteorological data

The only significant difference between the long-term climatic averages and the 03/04 season was the above average rainfall total in January followed by below average rainfall in February and March (Table 3.4).

Table 3.4. Mean monthly meteorological data for Forthside from September to March in 03/04 with long term averages in brackets.

Month - Year	Min. Temp. (degC)		Max. Temp. (degC)		Rainfall Total (mm)	
September-03	4.8	(4.9)	12.9	(13.3)	117.8	(98.3)
October-03	5.8	(6.2)	14.6	(15.4)	32.2	(84.9)
November-03	9.3	(8.1)	18.1	(17.1)	21.6	(69.5)
December-03	11.5	(9.6)	20.6	(18.9)	73.6	(67.5)
January-04	10.4	(11.0)	20.1	(20.6)	161.7	(54.4)
February-04	12.0	(11.6)	21.4	(21.0)	13.7	(45.8)
March-04	10.0	(10.4)	20.0	(19.8)	31.0	(55.5)

3.3.2 Onion yield and quality

There were no significant yield differences between the various neighbouring plant configurations in this experiment (Table 3.5) (F= 0.91, df=4, P=0.4668). While there appears to be a trend favouring the monoculture, experimental errors were too large to show a significant difference.

Table 3.5. Mean weight (kg) of onion samples with various neighbouring plant configurations.

Neighbouring plant row	Number (n)	Mean onion weight ± SE
Onion monoculture	16	48.47 ± 0.949
Broccoli edges	10	38.59 ± 1.828
Potato edges	10	35.91 ± 2.170
Plot edges	6	37.36 ± 2.160
Middle strip rows	12	37.01 ± 2.200

When the yield results were broken down into five size gradings, there were also no significant differences between the various neighbouring plant configurations (Table 3.6), although the 50mm size onions grown next to broccoli were approaching significance when compared to edge rows and the middle strip cropping rows (P=0.0577).

Table 3.6. Mean weight (kg) of five onion size gradings (mm diameter) with various neighbouring plant configurations.

Neighbouring plant row	Number (n)	40mm ± SE	50mm ± SE	60mm ± SE	70mm ± SE	70+ mm ± SE
Onion monoculture	16	0.691±0.059	4.025 ± 0.301	11.90 ± 0.691	21.119 ± 0.731	10.47 ± 0.870
Broccoli edges	10	0.995 ± 0.139	4.745 ± 0.538	10.780 ± 0.867	15.450 ± 0.717	5.605 ± 1.619
Potato edges	10	0.665 ± 0.094	4.020 ± 0.426	9.650 ± 1.180	15.540 ± 1.159	5.525 ± 0.828
Plot edges	6	0.917 ± 0.119	3.567 ± 0.525	9.775 ± 1.032	14.967 ± 0.761	7.783 ± 2.028
Middle strip rows	12	0.738 ± 0.103	3.546 ± 0.267	9.846 ± 0.733	15.413 ± 1.156	6.479 ± 1.209
F		1.59	2.48	1.19	1.10	1.03
df		4	4	4	4	4
P		0.1948	0.0577	0.3273	0.3676	0.4025

Similarly, the planned contrasts of the yield results (Table 3.7) did not reveal any significant differences between onions grown in monoculture and strip cropped onions in different neighbouring plant configurations.

Table 3.7. Planned pairwise contrasts of neighbouring plant configurations and onions grown in monoculture (*df*=1).

Contrast	*F*	*P*
Broccoli edges vs. Onion monoculture	1.33	0.2546
Potato edges vs. Onion monoculture	2.44	0.1255
Plot edges vs. Onion monoculture	2.86	0.0980
Strip middle rows vs. Onion monoculture	1.74	0.1946
Strip cropping vs. Monoculture	1.94	0.1704

When these planned contrasts were performed on the five different size gradings (Table 3.8), onions grown in the monoculture produced significantly more than the plot edges in the 60mm and 70mm size ranges (*P*=0.0469 and *P*=0.0450 respectively).

Table 3.8. Planned pairwise contrasts of five different size gradings of neighbouring plant configurations and onions grown in monoculture (*df*=1). Significant results are shown in bold type.

Contrast	40mm ± SE		50mm ± SE		60mm ± SE		70mm ± SE		70+mm ± SE	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Broccoli edges vs. Onion monoculture	0.04	0.8432	0.01	0.9253	1.84	0.1825	2.89	0.0961	0.98	0.3286
Potato edges vs. Onion monoculture	0.48	0.4929	0.31	0.5804	2.57	0.1162	2.41	0.1278	0.71	0.4052
Plot edges vs. Onion monoculture	0.18	0.6724	2.1	0.1549	4.19	**0.0469**	4.26	**0.0450**	2.56	0.1167
Strip middle rows vs. Onion monoculture	0.39	0.5364	1.68	0.2022	2.93	0.0941	2.45	0.1251	1.9	0.1749
Strip cropping vs. Monoculture	0.15	0.7026	0.45	0.5068	2.60	0.1141	2.77	0.1032	1.23	0.2744

The biggest difference in the onion yield results and the planned contrasts was a very significant plot effect (*F*=8.13, *df*=6, *P*<0.0001). The mean onion sample data from each plot (Table 3.9) illustrates that the harvest yields were not evenly distributed across the trial

plots. The monoculture plot (Plot 1) had the highest yield, which was significantly different to all other plots. The removal of the large plot effect in the ANOVA model made further analysis of the effect of neighbouring plants difficult. There also appeared to be a yield gradient favouring the eastern and central strip cropped Plots 2, 4 and 5, over the western most Plots 7, 8 and 9. When the lowest yielding plot (Plot 9) was removed from the analysis there remained significant differences between the monoculture plot and the strip cropping plots (F=4.72, df=5, P=0.0019). This significance was eliminated when Plots 7, 8 and 9 were removed from the analysis (F=0.96, df=3, P=0.4247). However, the removal of plot data did not result in any significant neighbouring plant interactions or significant pairwise contrasts.

Table 3.9. Mean weight of onion samples per plot (kg). Plots without a superscript letter in common are significantly different (P=0.05).

Plot	Strip arrangement	Number (n)	Mean onion weight ± SE
1	Onion Monoculture	18	47.86 ± 0.940 [a]
2	BOPBOP	6	43.05 ± 1.847 [b]
4	POBPOB	6	40.31 ± 1.376 [b]
5	OBPOBP	6	40.78 ± 1.276 [b]
7	BPOBPO	6	34.76 ± 2.651 [c]
8	PBOPBO	6	33.29 ± 1.981 [cd]
9	OPBOPB	6	29.02 ± 1.497 [d]

Key: P=Potatoes, O=Onions, B=Broccoli.

When the plot samples were graded for size, the yield differences between the monoculture and the strip cropped plots were not evenly distributed across the five different sizes (Table 3.10). Most of the differences between the monoculture plot and the strip cropped plots appeared in the two biggest gradings (70mm and 70mm+), with the exception of Plot 2 which was not significantly different to the monoculture. Plot 5 had the highest yields in the 40mm, 50mm and 60mm gradings. The 40mm and the 50mm gradings were significantly higher than all other plots, while the 60mm grade was significantly higher than all others except Plot 4.

Table 3.10. Mean weight (kg) of five onion size gradings (diameter in mm) per plot. Significant results are shown in bold type. Plots in grading columns without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip arrangement	Number (n)	40mm ± SE	50mm ± SE	60mm ± SE	70mm ± SE	70+ mm ± SE
1	Monoculture	18	0.70 ± 0.053 ^{bc}	3.91 ± 0.290 ^{bc}	11.54 ± 0.66 ^{b}	20.67 ± 0.712 ^{a}	10.84 ± 0.811 ^{a}
2	BOPBOP	6	0.70 ± 0.081 ^{bc}	2.93 ± 0.221 ^{cd}	7.42 ± 0.40 ^{c}	18.83 ± 0.649 ^{ab}	12.38 ± 1.608 ^{a}
4	POBPOB	6	0.87 ± 0.138 ^{b}	4.67 ± 0.336 ^{b}	11.83 ± 0.77 ^{ab}	17.46 ± 0.761 ^{bc}	4.48 ± 0.604 ^{bc}
5	OBPOBP	6	1.28 ± 0.194 ^{a}	5.73 ± 0.540 ^{a}	14.01 ± 0.44 ^{a}	16.04 ± 1.053 ^{cd}	2.93 ± 0.571 ^{c}
7	BPOBPO	6	0.68 ± 0.099 ^{bc}	4.34 ± 0.328 ^{b}	10.80 ± 0.89 ^{b}	14.45 ± 1.114 ^{de}	3.73 ± 0.655 ^{bc}
8	PBOPBO	6	0.94 ± 0.092 ^{b}	4.18 ± 0.306 ^{b}	9.93 ± 0.59 ^{b}	12.96 ± 0.944 ^{e}	4.48 ± 0.795 ^{bc}
9	OPBOPB	6	0.44 ± 0.068 ^{c}	2.41 ± 0.239 ^{d}	6.63 ± 0.53 ^{c}	11.96 ± 0.762 ^{e}	6.69 ± 0.930 ^{b}
F			5.17	8.13	8.85	5.72	10.32
df			6	6	6	6	6
P			**0.0004**	**<0.0001**	**<0.0001**	**0.0002**	**<0.0001**

Key: P=Potatoes, O=Onions, B=Broccoli.

3.3.3 Potato yield and quality

There were no significant differences in potato yields between the various neighbouring plant configurations (Table 3.11) (*F*=0.78, *df*=7, *P*=0.6096).

Table 3.11. Mean weight (kg) of potato samples with various neighbouring plant configurations.

Neighbouring plant	Number (n)	Mean potato weight (kg) ± SE
Potato monoculture	32	12.41 ± 1.532
Outer broccoli edges	10	10.87 ± 1.149
Inner broccoli edges	10	14.46 ± 1.602
Outer onion edges	10	13.00 ± 1.013
Inner onion edges	10	11.58 ± 0.968
Outer plot edges	6	13.68 ± 1.311
Inner plot edges	6	13.38 ± 1.446
Middle strip rows	24	15.24 ± 0.362

For processing potatoes like Russet Burbanks, tubers in the 850g-250g size range are considered to be “premium” tubers, while the 250g-75g are considered to be of processing

size and tubers under 75g are unacceptable and grouped as “rejects” together with tubers that exhibit some form of defect. When the potato yield results were partitioned into these three categories (Table 3.12), there were no significant yield differences between the various neighbouring plant configurations.

Table 3.12. Mean weight (kg) of three potato quality categories with various neighbouring plant configurations.

Neighbouring plant	Number (n)	850g-250g	250g-75g	Rejects
Potato monoculture	32	7.001 ± 0.259	7.142 ± 0.301	1.635 ± 0.103
Outer broccoli edges	10	5.488 ± 1.196	6.004 ± 0.569	2.288 ± 0.252
Inner broccoli edges	10	4.750 ± 0.832	5.162 ± 0.339	1.625 ± 0.308
Outer onion edges	10	6.372 ± 0.848	6.430 ± 0.616	1.736 ± 0.233
Inner onion edges	10	5.800 ± 0.834	6.549 ± 0.868	1.739 ± 0.227
Outer plot edges	6	6.647 ± 0.959	6.868 ± 1.135	1.896 ± 0.133
Inner plot edges	6	6.473 ± 0.520	5.664 ± 0.870	1.915 ± 0.346
Middle strip rows	24	5.495 ± 0.483	5.116 ± 0.539	2.170 ± 0.221
F		0.32	0.97	1.15
df		7	7	7
P		0.9437	0.4608	0.3407

When the reasons for the rejections were ranked from one to four, with one being the defect with the lowest incidence in the sample and four being the defect with the highest incidence (Table 3.13), there were no significant differences between the defects, “small”, “green” and “knobby”. The five other rejection defects, “hollow”, “rot”, “grub”, “cracks” and “damage” were too infrequent to be analysed.

Table 3.13. Mean weight (kg) of potato rejection categories with various neighbouring plant configurations.

Neighbouring plant	Number (n)	Small ± SE	Green ± SE	Knobby ± SE
Potato monoculture	32	2.406 ± 0.287	2.125 ± 0.245	1.531 ± 0.273
Outer broccoli edges	10	1.200 ± 0.611	3.300 ± 0.213	2.200 ± 0.291
Inner broccoli edges	10	2.500 ± 0.543	2.900 ± 0.379	1.600 ± 0.499
Outer onion edges	10	2.000 ± 0.577	2.400 ± 0.221	2.100 ± 0.504
Inner onion edges	10	2.200 ± 0.533	2.800 ± 0.249	1.700 ± 0.539
Outer plot edges	6	2.333 ± 0.667	3.000 ± 0.365	0.833 ± 0.654
Inner plot edges	6	2.333 ± 0.760	3.000 ± 0.516	1.500 ± 0.563
Middle strip rows	24	1.708 ± 0.316	2.917 ± 0.255	2.292 ± 0.237
F		0.67	1.31	0.81
df		7	7	7
P		0.6980	0.2523	0.5816

Planned contrasts of the potato yields did not reveal any significant differences between potatoes grown in monoculture and strip cropped potatoes in different neighbouring plant configurations (Table 3.14).

Table 3.14. Planned pairwise contrasts of various neighbouring plant configurations and potatoes grown in monoculture (*df*=1).

Contrast	*F*	*P*
Both broccoli edge rows vs. Potato monoculture	0.23	0.6294
Outer broccoli edge rows vs. Potato monoculture	0.01	0.9117
Both onion edge rows vs. Potato monoculture	0.00	0.9959
Outer onion edge rows vs. Potato monoculture	0.01	0.9429
Both plot edge rows vs. Potato monoculture	0.18	0.6734
Outer plot edge rows vs. Potato monoculture	0.00	0.9803
Middle strip rows vs. Potato monoculture	0.64	0.4255
Strip Cropping vs. Monoculture	0.13	0.7175

Planned contrasts of the three different quality categories (Table 3.15) also resulted in no significant differences between potatoes grown in monoculture and potatoes grown in various neighbouring plant configurations.

Table 3.15. Planned pairwise contrasts of potato quality categories of various neighbouring plant configurations and potatoes grown in monoculture (*df*=1).

Contrast	850g-250g		250g-75g		Rejects	
	F	***P***	***F***	***P***	***F***	***P***
Both broccoli edge rows vs. Potato monoculture	0.05	0.8175	0.26	0.6102	0.09	0.7646
Both onion edge rows vs. Potato monoculture	0.03	0.8617	0.01	0.9148	0.56	0.4547
Outer broccoli edge rows vs. Potato monoculture	0	0.9634	0.04	0.8517	0.18	0.6744
Outer onion edge rows vs. Potato monoculture	0.14	0.7106	0.02	0.8856	0.52	0.4718
Both plot edge rows vs. Potato monoculture	0	0.9567	0.2	0.6530	0.04	0.8393
Outer plot edge rows vs. Potato monoculture	0	0.9788	0.01	0.9105	0.01	0.9131
Middle strip rows vs. Potato monoculture	0.04	0.8328	1.04	0.3100	0	0.9821
Strip cropping vs. Monoculture	0	0.9468	0.22	0.6422	0.19	0.6601

Similar to the onion yield results, the statistical analysis of the potato yield results was hindered by a very significant plot effect (F= 9.65, df=6, P<0.0001). The correction of the plot effect in the ANOVA model again made the analysis of any neighbouring plant categories difficult. The comparison of the average plot weight of the potatoes sampled (Table 3.16) indicated that there was a yield gradient favouring the Plots 2, 3, 4 and 5 over the western most plots (Plots 7, 8 and 9). However, unlike the onion results, the monoculture plot (Plot 3) did not yield significantly more than all the strip cropped plots.

The removal of the lowest yielding plot (Plot 8) reduced the F statistic from 9.65 to 5.92, but did not raise the statistical significance above the SAS packages minimum of P<0.0001 (df=5). Further removal of Plots 7 and 9 from the analysis resulted in no significant differences between the plots (F=0.75. df=3, P=0.5249). However, like the onion results, the removal of low yielding plots from the analysis did not result in any significant neighbouring plant interactions or significant pairwise contrasts.

Table 3.16. Mean weight of the potato samples per plot (kg). Plots without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip arrangement	Number (n)	Mean potato weight (kg)
2	BOPBOP	12	14.969 ± 0.833 [a]
3	Monoculture	36	15.164 ± 0.343 [a]
4	POBPOB	12	15.740 ± 0.822 [a]
5	OBPOBP	12	13.957 ± 0.868 [a]
7	BPOBPO	12	10.519 ± 1.067 [b]
8	PBOPBO	12	7.698 ± 1.040 [c]
9	OPBOPB	12	11.111 ± 1.082 [b]
Key: P=Potatoes, O=Onions, B=Broccoli.			

The size range plot data indicated that the plots that yielded the most (Strip cropping Plots 2, 4 and 5; and the Plot 3 monoculture) did so by producing the most premium sized tubers i.e. 850g-250g (Table 3.17).

Table 3.17 Mean plot weights (kg) of three potato quality categories. Significant results are shown in bold type. Plots in category columns without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip arrangement	Number (n)	850g-250g ± SE	250g-75g ± SE	Rejects ± SE
2	BOPBOP	12	6.737 ± 0.432 [a]	6.928 ± 0.562 [a]	2.310 ± 0.374 [ab]
3	Monoculture	36	6.994 ± 0.252 [a]	7.089 ± 0.270[a]	1.626 ± 0.096 [bc]
4	POBPOB	12	8.117 ± 0.681 [a]	6.579 ± 0.489 [a]	2.119 ± 0.184 [ab]
5	OBPOBP	12	6.870 ± 0.617 [a]	6.143 ± 0.708 [ab]	2.456 ± 0.261 [a]
7	BPOBPO	12	4.932 ± 0.628 [b]	4.927 ± 0.514 [bc]	1.533 ± 0.173 [c]
8	PBOPBO	12	3.490 ± 0.583 [b]	3.534 ± 0.629 [c]	1.486 ± 0.154 [c]
9	OPBOPB	12	3.765 ± 0.579 [b]	6.284 ± 0.713 [ab]	1.981 ± 0.257 [ab]
F			8.93	4.06	2.84
df			6	6	6
P			**<0.0001**	**<0.0001**	**0.0139**
Key: P=Potatoes, O=Onions, B=Broccoli.					

Although the analysis of the rejection rankings did result in significant plot differences for both “small” and “green” tubers, these did not appear to be related to the differences in yield (Table 3.18). Differences between the number of “knobby” potatoes in each plot were not significant and the five other rejection defects, “hollow”, “rot”, “grub”, “cracks” and “damage” were again too infrequent to be analysed.

Table 3.18. Mean plot rejection rankings for harvested potatoes. Significant results are shown in bold type. Plots in category columns without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip arrangement	Number (n)	Small ± SE	Green ± SE	Knobby ± SE
2	BOPBOP	12	1.750 + 0.494 ^{b}	3.250 ± 0.179 ^{a}	1.833 ± 0.423
3	Monoculture	36	2.472 ± 0.266 ^{ab}	2.278 ± 0.231 ^{bc}	1.444 ± 0.250
4	POBPOB	12	1.917 ± 0.514 ^{b}	2.667 ± 0.310 ^{abc}	2.167 ± 0.423
5	OBPOBP	12	1.583 ± 0.434 ^{b}	3.417 ± 0.229 ^{a}	2.333 ± 0.396
7	BPOBPO	12	1.333 ± 0.497 ^{b}	2.667 ± 0.333 ^{abc}	2.417 ± 0.398
8	PBOPBO	12	1.333 ± 0.512 ^{b}	3.083 ± 0.229 ^{ab}	1.583 ± 0.417
9	OPBOPB	12	3.417 ± 0.229 ^{a}	2.083 ± 0.358 ^{c}	1.500 ± 0.359
F			2.58	2.27	0.83
df			6	6	6
P			**0.0236**	**0.0429**	0.5515
Key: P=Potatoes, O=Onions, B=Broccoli.					

3.3.4 Broccoli yield

In contrast to both onions and potatoes, there were significant differences between the broccoli yield results for the various neighbouring plant configurations (Table 3.19) (*F*=3.24, *df*=7, *P*=0.0040).

Table 3.19. Mean head weight (kg) of broccoli with various neighbouring plant configurations. Neighbouring plants without a superscript letter in common are significantly different (*P*=0.05).

Neighbouring plant	Number (n)	Mean broccoli head weight (kg) ± SE
Broccoli monoculture	32	0.3351 ± 0.0051 ^{abc}
Outer potato edges	10	0.3390 ± 0.0077 ^{ab}
Inner potato edges	10	0.3163 ± 0.0116 ^{cd}
Outer onion edges	10	0.3330 ± 0.0063 ^{abcd}
Inner onion edges	10	0.3132 ± 0.0062 ^{d}
Outer plot edges	6	0.3532 ± 0.0116 ^{a}
Inner plot edges	6	0.3209 ± 0.0140 ^{bcd}
Middle strip rows	24	0.3151 ± 0.0061 ^{cd}

As the broccoli was harvested in four separate cuts, the harvest data was broken down into the percentage of the total harvest at each cut (Table 3.20). There were significant differences between the rates of maturity of the different neighbouring plant configurations at cuts 1, 2 and 4. The LSD groupings indicate that the broccoli rows immediately adjacent to onion strips (onion outer edge) and the middle rows of the strip cropped broccoli (middle strip rows) produced most of their yield earlier than the other neighbouring plant configurations.

Table 3.20. Percentage of the total broccoli harvest at each cut compared to neighbouring plant configurations. Significant results are shown in bold type. Neighbours within columns without a superscript letter in common are significantly different (*P*=0.05).

Neighbour	Number	Cut 1	Cut 2	Cut 3	Cut 4
Broccoli monoculture	32	2.52 ± 0.370 ^{abcd}	21.65 ± 1.938 ^{cd}	47.76 ± 1.558	28.08 ± 2.314 ^{bc}
Outer potato edges	10	1.10 ± 0.506 ^{cd}	25.64 ± 3.494 ^{bcd}	40.33 ± 3.755	32.92 ± 4.939 ^{ab}
Inner potato edges	10	0.61 ± 0.330 ^{d}	20.02 ± 3.857 ^{d}	40.48 ± 2.931	38.89 ± 5.069 ^{a}
Outer onion edges	10	4.14 ± 1.542 ^{a}	41.18 ± 3.688 ^{a}	35.45 ± 2.767	19.23 ± 4.178 ^{cd}
Inner onion edges	10	1.93 ± 0.949 ^{bcd}	30.27 ± 4.816 ^{bc}	40.54 ± 3.143	27.27 ± 4.911 ^{cd}
Outer plot edges	6	3.20 ± 1.078 ^{abc}	30.40 ± 6.316 ^{bc}	37.56 ± 3.685	28.84 ± 8.271 ^{abc}
Inner plot edges	6	1.89 ± 1.146 ^{abcd}	24.77 ± 6.183 ^{cd}	41.58 ± 2.895	31.76 ± 7.701 ^{ab}
Middle strip rows	24	3.91 ± 0.786 ^{ab}	35.19 ± 3.313 ^{ab}	43.31 ± 2.742	17.59 ± 2.566 ^{d}
F		2.60	2.99	0.99	4.15
df		6	6	6	6
P		**0.0171**	**0.0070**	0.4441	**0.0005**

Several planned pairwise contrasts were significant for the broccoli results (Table 3.21). The interaction of broccoli and potatoes on the outer potato edge row resulted in broccoli producing, on average, heavier heads when compared to broccoli grown in monoculture. However, when the first two potato edge rows were grouped the monoculture produced heavier broccoli heads, albeit at a lower level of significance. A similar effect was also evident for the plot edges. Conversely, the first row of broccoli grown next to onions had significantly smaller average head weights compared to broccoli grown in monoculture, although this effect did not penetrate into the second edge row. It appears that only the edge rows exhibited any significant effects because the middle rows and strip cropping in general were not significantly different from broccoli grown in monoculture. However, the contrast of monoculture and strip cropping was approaching significance, which would have resulted in monoculture producing on average head of 0.335 kg compared to strip cropping producing 0.321kg.

Table 3.21. Planned pairwise contrasts of broccoli yield and the various neighbouring plant configurations and broccoli grown in monoculture (*df*=1). Significant results are shown in bold type.

Contrast	*F*	*P*
Both potato edge rows vs. Broccoli monoculture	4.76	**0.0317**
Outer potato edge rows vs. Broccoli monoculture	7.44	**0.0076**
Both onion edge rows vs. Broccoli monoculture	3.09	0.0819
Outer onion edge rows vs. Broccoli monoculture	5.03	**0.0273**
Both plot edge rows vs. Broccoli monoculture	5.97	**0.0164**
Outer plot edge rows vs. Broccoli monoculture	10.61	**0.0016**
Middle strip rows vs. Broccoli monoculture	1.90	0.1708
Strip cropping vs. Monoculture	3.68	0.0580

These contrasts were only significant for the pooled harvest data (that is, all four cuts), as an examination of the planned contrasts at each cut did not show any significant differences (Table 3.22).

Table 3.22. Planned pairwise contrasts of the fraction of the total harvest at each broccoli cut from the various neighbouring plant configurations and broccoli grown in monoculture (*df*=1).

Contrast	Cut 1		Cut 2		Cut 3		Cut 4	
	F	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Both potato edge rows vs. Broccoli monoculture	1.45	0.2314	0.40	0.5279	0.46	0.4995	2.08	0.1530
Outer potato edge rows vs. Broccoli monoculture	1.02	0.3156	0.07	0.7963	0.42	0.5192	0.98	0.3246
Both onion edge rows vs. Broccoli monoculture	0.06	0.8109	0.62	0.4347	1.19	0.2789	0.05	0.8243
Outer onion edge rows vs. Broccoli monoculture	0.15	0.7007	2.06	0.1541	1.94	0.1665	0.07	0.7885
Both plot edge rows vs. Broccoli monoculture	0.15	0.7008	0.04	0.8478	0.79	0.3771	0.39	0.5315
Outer plot edge rows vs. Broccoli monoculture	0.01	0.9277	0.35	0.5552	1.23	0.2703	0.12	0.7315
Middle strip rows vs. Broccoli monoculture	0.17	0.6804	0.82	0.3685	0.03	0.8618	0.59	0.4458
Strip cropping vs. Monoculture	0.27	0.6076	0.06	0.8048	0.59	0.4434	0.29	0.5947

Similar to the onion and potato yield results, the statistical analysis of the broccoli yield results was hindered by a very significant plot effect (F= 7.61, df=6, P<0.0001) (Table 3.23). The correction of the plot effect in the ANOVA model again made the analysis of any neighbouring plant categories difficult. The comparison of the average head weight per plot indicated that there were significantly lower yields in Plots 2, 8 and 9 and the monoculture plot was not significantly different from Plots 4, 5 and 7.

Table 3.23. Mean broccoli head weight per plot (kg) ± SE. Plots without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip arrangement	Number	Mean broccoli head weight ± SE
2	BOPBOP	12	0.3142 ± 0.0076 [b]
4	POBPOB	12	0.3370 ± 0.0057 [a]
5	OBPOBP	12	0.3400 ± 0.0061 [a]
6	Monoculture	36	0.3386 ± 0.0051 [a]
7	BPOBPO	12	0.3358 ± 0.0065 [a]
8	PBOPBO	12	0.3095 ± 0.0064 [bc]
9	OPBOPB	12	0.2935 ± 0.0076 [c]
Key: P=Potatoes, O=Onions, B=Broccoli.			

There were also significant plot differences between the rates of maturity at each of the cuts (Table 3.24). The LSD groupings indicate that Plot 4 was the fastest maturing with the plot's highest percentage yield in the second cut, while Plot 9 was the slowest maturing with the plot's highest percentage yield coming at the final cut.

Table 3.24. Percentage of the total broccoli harvest at each cut per plot. Significant results are shown in bold type. Plots within columns without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip arrangement	Number (n)	Cut 1	Cut 2	Cut 3	Cut 4
2	BOPBOP	12	1.93 ± 0.664 [bcd]	30.14 ± 2.704 [b]	44.90 ± 2.078 [ab]	23.03 ± 2.783 [bc]
4	POBPOB	12	6.65 ± 1.632 [a]	45.79 ± 4.603 [a]	32.18 ± 3.985 [c]	15.38 ± 2.981 [c]
5	OBPOBP	12	3.60 ± 0.675 [b]	33.24 ± 3.265 [b]	46.73 ± 3.172 [a]	16.43 ± 2.631 [c]
6	Monoculture	36	2.46 ± 0.331 [bc]	21.77 ± 1.862 [c]	47.26 ± 1.468 [a]	28.50 ± 2.195 [b]
7	BPOBPO	12	2.63 ± 0.745 [bc]	36.82 ± 3.947 [b]	37.69 ± 2.787 [bc]	22.86 ± 4.334 [bc]
8	PBOPBO	12	1.18 ± 0.394 [cd]	29.50 ± 2.719 [bc]	43.46 ± 2.416 [ab]	25.86 ± 3.570 [b]
9	OPBOPB	12	0.19 ± 0.187 [d]	12.46 ± 2.723 [d]	37.45 ± 2.801 [bc]	49.90 ± 4.456 [a]
F			7.53	9.78	3.26	11.86
df			6	6	6	6
P			**<0.0001**	**<0.0001**	**0.0058**	**<0.0001**
Key: P=Potatoes, O=Onions, B=Broccoli.						

The removal of the lowest yielding plot (Plot 9) from the pooled harvest data reduced the significance of the yield difference to P=0.0013 (F=4.40, df=5). The subsequent removal of all the lower yielding plots (Plots 2, 8 and 9), eliminated the significant difference between the remaining plots (F=1.06, df=3, P=0.3710) and the neighbouring plant configurations (F=1.49, df=7, P=0.1863).

Re-analysis of the data with the lowest yielding plots removed, reduced the number of significant planned contrasts with only the outer edge rows being significantly different to the broccoli monoculture (Table 3.25).

Table 3.25. Planned pairwise contrasts of various neighbouring plant configurations and broccoli grown in monoculture with all plots included and with the lowest yielding plots removed (*df*=1). Significant results are shown in bold type.

Contrast	All Plots		Plots 2, 8 and 9 removed	
	F	***P***	***F***	***P***
Both potato edge rows vs. Broccoli monoculture	4.76	**0.0317**	3.05	0.0860
Outer potato edge rows vs. Broccoli monoculture	7.44	**0.0076**	2.98	0.0892
Both onion edge rows vs. Broccoli monoculture	3.09	0.0819	1.41	0.2404
Outer onion edge rows vs. Broccoli monoculture	5.03	**0.0273**	1.76	0.1897
Both plot edge rows vs. Broccoli monoculture	5.97	**0.0164**	5.27	**0.0252**
Outer plot edge rows vs. Broccoli monoculture	10.61	**0.0016**	8.88	**0.0041**
Middle strip rows vs. Broccoli monoculture	1.90	0.1708	2.03	0.1595
Strip cropping vs. Monoculture	3.68	0.0580	2.35	0.1304

The low incidence of odd shaped broccoli heads meant that statistical analysis of this defect was not possible.

3.3.5 Diseases in onions

The onion crop was infected by downy mildew (*Peronospora destructor*) (Picture 3.16), which radiated from Plot 5 resulting in significant differences between the infection rates on each plot (F= 13.02, df=6, P<0.0001)(Table 3.26). Although infection rates were assessed for each row in the experiment and the location of the infected plants recorded, the large number of infected plants in Plot 5 made counting the number of infected plants

impractical. Therefore the number of infected plants in Plot 5 was estimated based on the approximate area of infected plants multiplied by the number of plants per square metre and the data log +1 transformed before analysis.

Picture 3.16. Downy mildew (*P. destructor*) symptoms.

Table 3.26. Schematic of plots and number of plants per strip with downy mildew infection (*P. destructor*). Plots without a superscript letter in common are significantly different (*P*=0.05).

Plot 1 **Onion** **Monoculture** 13.50 ± 3.41 [b]	**Plot 2** **Strip Crop** **BOPBOP** 22.50 ± 9.63 [b]	**Plot 3** **Potato** **Monoculture**
Plot 4 **Strip Crop** **POBPOB** 25.67 ± 8.49 [b]	**Plot 5** **Strip Crop** **OBPOBP** 1448.00 ± 129.49 [a]	**Plot 6** **Broccoli** **Monoculture**
Plot 7 **Strip Crop** **BPOBPO** 5.17 ± 1.90 [b]	**Plot 8** **Strip Crop** **PBOPBO** 46.33 ± 15.11 [b]	**Plot 9** **Strip Crop** **PBOPBO** 20.00 ± 4.20 [b]

Key: P=Potatoes, O=Onions, B=Broccoli.

The removal of Plot 5 from the analysis (Table 3.27) reduced the significance level of the differences between the plots (*F*=2.61, *df*=5, *P*=0.0428). This test indicated a trend with the

nearest plots to the main site of infection (Plots 2, 4 and 8) having higher infection rates than the plots furthest away from the outbreak (Plots 1, 7 and 9).

Table 3.27. Mean downy mildew (*P. destructor*) incidence with Plot 5 removed. Plots without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip Arrangement	Number (n)	Mean number of infected plants
1	Monoculture	18	13.50 ± 3.41 [b]
2	BOPBOP	6	22.50 ± 9.63 [b]
4	POBPOB	6	25.67 ± 8.49 [ab]
7	BPOBPO	6	5.17 ± 1.90 [b]
8	PBOPBO	6	46.33 ± 15.11 [a]
9	OPBOPB	6	20.00 ± 4.20 [b]
Key: P=Potatoes, O=Onions, B=Broccoli.			

The high number of infected plants in Plot 5 made the analysis of the effect of neighbouring plant configurations (Table 3.28) (F=0.28, df=4, P=0.8865) and the planned pairwise contrasts insignificant (Table 3.29).

Table 3.28. Mean downy mildew (*P. destructor*) incidence compared to neighbouring plant configurations.

Neighbouring plant	Number (n)	Non transformed data ± SE	Transformed data (Log +1) ± SE
Onion monoculture	16	14.875 ± 3.688	2.093 ± 0.351
Broccoli edges	10	338.200 ± 207.146	3.746 ± 0.690
Potato edges	10	192.100 ± 167.826	3.173 ± 0.607
Plot edges	6	148.333 ± 136.035	2.791 ± 0.929
Middle strip rows	12	268.167 ± 166.480	3.312 ± 0.626

Table 3.29. Planned pairwise contrasts of downy mildew (*P. destructor*) incidence and various neighbouring plant configurations and onion monoculture (*df*=1).

Contrast	*F*	*P*
Broccoli edge vs. Onion monoculture	0.88	0.3546
Potato edge vs. Onion monoculture	0.82	0.3718
Plot edges vs. Onion monoculture	0.49	0.4887
Strip middle rows vs. Onion monoculture	1.10	0.3008
Monoculture vs. Strip Cropping	0.99	0.3251

The subsequent removal of Plot 5 results from the analysis of the neighbouring plants (Table 3.30) (F=0.22, df=4, P=0.9266) and the planned comparisons (Table 3.31) did not result in any significant tests.

Table 3.30. Mean downy mildew (*P. destructor*) incidence compared to neighbouring plant configurations with Plot 5 results removed.

Neighbouring plant	Number (n)	Non transformed data ± SE
Onion monoculture	16	14.88 ± 3.688
Broccoli edge	8	28.25 ± 10.32
Potato edge	9	24.44 ± 8.458
Plot edges	5	12.40 ± 6.454
Middle strip rows	10	21.50 ± 8.024

Table 3.31. Planned pairwise contrasts of the average downy mildew (*P. destructor*) incidence and various neighbouring plant configurations and onion monoculture with Plot 5 data removed (*df*=1).

Contrast	*F*	*P*
Broccoli edge vs. Onion monoculture	0	0.9691
Potato edge vs. Onion monoculture	0	0.9476
Plot edges vs. Onion monoculture	0.27	0.6063
Strip middle rows vs. Onion monoculture	0.05	0.8272
Monoculture vs. Strip cropping	2.70	0.1098

3.3.6 Diseases in potatoes

Analysis of the effects of strip cropping on the incidence of disease in potatoes was impossible due to the confounding effects of seed borne disease (an external factor outside of experimental control) with Plot 8 being the worst affected. Samples of diseased tubers were sent to the Tasmanian Department of Primary Industry Water and Environment's Plant Pathology laboratory in Hobart. The cause of the seed breakdown was determined to be a combination of the fungus *Fusarium* sp. and the bacterium *Erwinia* sp. (Metcalf D., Senior Plant Pathologist DPIWE, *pers. comm.* 2004). At harvest time there were no significant differences in the number of rotten tubers encountered in the different neighbouring plant configurations (F=0.61, df=7, P=0.7461) or plots (F=1.14, df=6, P=0.3450) and there were no significant planned contrasts.

3.3.7 Diseases in broccoli

The only disease encountered in the broccoli crops was white blister rust (*Albugo candida*). This is a relatively new disease of Brassica crops in Australia and was first located in the outer plot edge of Plot 7 on 10 December 2003 during the regular monitoring of the experimental area. Spread of the disease meant that at the time of the first harvest on the 9 January 2004, the disease was present in the entire experimental area. The main consequence of this disease is the rejection of broccoli heads due to visual presence of the rust fungus, which looks like white paint flecks (Picture 3.15). Therefore, the presence of the disease was only recorded after harvest as the percentage of the harvested heads rejected. The analysis of the broccoli harvest rejection rates due to the white blister rust indicated that there were significant differences between the neighbouring plant configurations (F=3.70, df=6, P=0.0015) (Table 3.32).

Table 3.32. Percentage of the broccoli harvest rejected due to white blister rust (*A. candida*) compared to neighbouring plant configurations. Neighbouring plants without a superscript letter in common are significantly different (*P*=0.05).

Neighbouring plant	Number (n)	Percentage of broccoli rejected ± SE
Broccoli monoculture	32	18.39 ± 1.559 [c]
Outer potato edges	10	18.11 ± 4.477 [c]
Inner potato edges	10	21.29 ± 4.598 [bc]
Outer onion edges	10	34.41 ± 4.198 [a]
Inner onion edges	10	33.37 ± 3.457 [a]
Outer plot edges	6	33.28 ± 7.674 [a]
Inner plot edges	6	28.70 ± 6.379 [ab]
Middle strip rows	24	30.95 ± 2.308 [a]

Further analysis of the results over the four broccoli cuts revealed that most of the differences in the harvest rejection rates occurred in the final two cuts (Table 3.33).

Table 3.33. Neighbouring plant row comparisons of the percentage of broccoli heads rejected at each cut due to infection with white blister rust (*A. candida*). Significant results are shown in bold type. Neighbouring plants within columns without a superscript letter in common are significantly different (*P*=0.05).

Neighbouring plant	Number (n)	Cut 1	Cut 2	Cut 3	Cut 4
Broccoli monoculture	32	14.53 ± 4.815	36.13 ± 3.231	14.63 ± 1.777 [c]	14.25 ± 1.947 [b]
Outer potato edges	10	3.33 ± 3.333	35.40 ± 9.155	18.16 ± 5.923 [c]	11.82 ± 2.928 [b]
Inner potato edges	10	0.00 ± 0.00	29.39 ± 4.666	24.55 ± 6842 [bc]	18.85 ± 6.295 [b]
Outer onion edges	10	12.81 ± 6.327	42.82 ± 7262	36.58 ± 6.396 [ab]	19.42 ± 4.543 [b]
Inner onion edges	10	1.00 ± 1.000	44.78 ± 7.331	42.31 ± 4.356 [a]	14.55 ± 2.987 [b]
Outer plot edges	6	11.27 ± 5.637	37.91 ± 8.464	35.95 ± 9316 [ab]	36.16 ± 14.79 [a]
Inner plot edges	6	2.38 ± 2.381	45.50 ± 6.346	30.21 ± 9.194 [ab]	17.38 ± 2.761 [b]
Middle strip rows	24	8.62 ± 2.864	38.54 ± 2.713	34.36 ± 2.900 [ab]	25.66 ± 4.183 [b]
F		0.52	0.91	3.49	2.37
df		7	7	7	7
P		0.8156	0.5061	**0.0024**	**0.0286**

However, these differences were not significant when the neighbouring plant configurations were individually contrasted with the broccoli monoculture results (Table 3.34).

Table 3.34. Planned pairwise contrasts of the percentage of harvested broccoli heads rejected due to white blister rust (*A. candida*) of various neighbouring plant configurations and broccoli monoculture (*df*=1).

Contrast	*F*	*P*
Both potato edge rows vs. Broccoli monoculture	2.57	0.1126
Outer potato edge rows vs. Broccoli monoculture	3.03	0.0854
Both onion edge rows vs. Broccoli monoculture	0.18	0.6710
Outer onion edge rows vs. Broccoli monoculture	0.24	0.6274
Both plot edge rows vs. Broccoli monoculture	0.64	0.4270
Outer plot edge rows vs. Broccoli monoculture	1.17	0.2820
Middle strip rows vs. Broccoli monoculture	0	0.9865
Strip cropping vs. Monoculture	0.24	0.6244

Analysis of the contrasts at each cut also did not indicate any significant differences (Table 3.35).

Table 3.35. Planned pairwise contrasts of the percentage of broccoli heads rejected at each cut due to white blister rust (*A. candida*) of various neighbouring plant configurations and broccoli monoculture (*df*=1).

Contrast	Cut 1		Cut 2		Cut 3		Cut 4	
	F	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Both potato edge rows vs. Broccoli monoculture	1.46	0.2306	0.44	0.5093	2.34	0.1299	0.85	0.3587
Outer potato edge row vs. Broccoli monoculture	1.12	0.2937	0.08	0.7807	3.21	0.0765	1.35	0.2483
Both onion edge rows vs. Broccoli monoculture	0.94	0.3361	0.06	0.8024	0.22	0.6416	0.61	0.4362
Outer onion edge row vs. Broccoli monoculture	0.34	0.5603	0.03	0.8521	0.03	0.8643	0.31	0.5786
Both plot edge rows vs. Broccoli monoculture	0.77	0.3823	0.34	0.5609	0.34	0.5639	0.59	0.4461
Outer plot edge rows vs. Broccoli monoculture	0.25	0.6183	0.64	0.4255	0.76	0.3867	3.58	0.0618
Middle strip rows vs. Broccoli monoculture	0.64	0.4259	0.17	0.6808	0.03	0.8725	0	0.9445
Strip cropping vs. Monoculture	1.14	0.2895	0.07	0.7991	0.22	0.6372	0.52	0.4726

White blister rust was present in all of the experimental broccoli plots, however the disease was concentrated in Plot 7 where it was first located (Table 3.36). This is illustrated by a significant difference between the plots (F=5.66, df=6, P<0.0001) with Plot 7 having the highest percentage of harvest rejection.

Table 3.36. Mean plot percentages of harvested broccoli heads rejected due to white blister rust (*A. candida*) ± SE. Plots without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip arrangement	Number (n)	Mean percentage of rejected broccoli ± SE
2	BOPBOP	12	33.29 ± 2.42 [b]
4	POBPOB	12	27.89 ± 3.67 [bc]
5	OBPOBP	12	21.79 ± 2.47 [cd]
6	Monoculture	36	18.87 ± 1.47 [d]
7	BPOBPO	12	42.60 ± 2.43 [a]
8	PBOPBO	12	32.35 ± 5.24 [b]
9	OPBOPB	12	16.71 ± 3.47 [d]
Key: P=Potatoes, O=Onions, B=Broccoli.			

Further analysis of the percentage of harvest rejection in each plot over the four cuts also reveals that the differences occurred in the final two cuts (Table 3.37).

Table 3.37. Mean plot percentages of harvested broccoli heads rejected at each cut due to infection with white blister rust (*A. candida*) ± SE. Significant results are shown in bold type. Plots within columns without a superscript letter in common are significantly different (*P*=0.05).

Plot	Strip arrangement	Number (n)	Cut 1 ± SE	Cut 2 ± SE	Cut 3 ± SE	Cut 4 ± SE
2	BOPBOP	12	8.61 ± 4.86	41.48 ± 4.68	38.33 ± 3.81 [b]	16.79 ± 1.42 [c]
4	POBPOB	12	9.60 ± 3.43	31.19 ± 4.33	30.80 ± 4.82 [bc]	29.24 ± 8.20 [ab]
5	OBPOBP	12	10.12 ± 5.17	25.44 ± 2.05	20.73 ± 3.92 [cd]	18.64 ± 3.62 [bc]
6	Monoculture	36	13.84 ± 4.36	36.24 ± 2.96	15.17 ± 1.69 [d]	14.93 ± 1.78 [c]
7	BPOBPO	12	4.46 ± 2.45	45.93 ± 3.29	50.80 ± 3.79 [a]	39.53 ± 8.96 [a]
8	PBOPBO	12	2.78 ± 2.78	42.50 ± 6.13	37.77 ± 6.09 [b]	14.56 ± 3.28 [c]
9	OPBOPB	12	0	46.86 ± 9.05	18.23 ± 4.57 [d]	8.53 ± 2.34 [c]
F			0.26	2.08	6.51	4.40
df			6	6	6	6
P			0.9539	0.0632	**<0.0001**	**0.0006**
Key: P=Potatoes, O=Onions, B=Broccoli.						

Removal of Plot 7 from the analysis resulted in a reduction in the level of significance to *P*=0.0091 (*F*=3.31, *df*=5). However, the significant differences between the neighbouring plant row configurations remained very significant (*F*=4.84, *df*=7, *P*=0.0001) and none of

the planned contrasts of the different neighbours were significant. However, broccoli growing immediately adjacent to potato rows and the second row next to potatoes were below *P*=0.1, at *P*=0.0856 and *P*=0.0790 respectively.

3.3.8 Insect pests

Monitoring of the three crops showed the presence of various insect pests specific to each crop. Insect pests recorded in the onion strips were cutworm (*Agrotis* spp.) and onion thrips (*Thrips tabaci*). The potato moth (*Phthorimaea operculella*) was the only insect pest observed in the potato crops. A range of insect pests was found in the broccoli crop including diamondback moth (*Plutella xylostella*), cabbage white butterfly (*Pieris rapae*) and cabbage aphid (*Brevicoryne brassicae.* Analysis of the diamondback moth data indicated that differences between the neighbouring plant configurations were approaching significance (*F*=2.02, *df*=6, *P*=0.0607)(Table 3.38).

Table 3.38. Neighbouring plant configurations and the incidence of diamondback moth (*P. xylostella*) larvae per plant.

Neighbouring plant	Number (n)	Incidence ± SE
Broccoli monoculture	32	2.156 ± 0.169
Outer potato edges	10	1.900 ± 0.277
Inner potato edges	10	1.800 ± 0.249
Outer onion edges	10	2.600 ± 0.306
Inner onion edges	10	2.000 ± 0.211
Outer plot edges	6	2.667 ± 0.211
Inner plot edges	6	1.500 ± 0.342
Middle strip rows	24	2.000 ± 0.147

However, the planned contrasts of the broccoli neighbouring plants configurations results did not reveal any significant differences (Table 3.39) and there were no significant differences between the numbers of diamondback moth in the different plots (*F*=0.60, *df*=6, *P*=0.7303).

Table 3.39. Planned pairwise contrasts of the incidence of diamondback moth (*P. xylostella*) in neighbouring plant row configurations and the broccoli monoculture (*df*=1).

Contrast	*F*	*P*
Both potato edge rows vs. Broccoli monoculture	2.79	0.0984
Outer potato edge row vs. Broccoli monoculture	2.27	0.1351
Both Onion edge rows vs. Broccoli monoculture	0.65	0.4222
Outer Onion edge row vs. Broccoli monoculture	0.08	0.7844
Both plot edge rows vs. Broccoli monoculture	1.55	0.2168
Outer plot edge rows vs. Broccoli monoculture	0	0.9917
Middle strip rows vs. Broccoli monoculture	1.96	0.1653
Strip cropping vs. Monoculture	1.73	0.1924

While the distribution of the remaining insects was not measured due to time constraints and low numbers, there also appeared to be no differences across the neighbouring plant configurations and there were no apparent adverse or beneficial effects due to the close proximity of different crops.

3.4 Discussion

3.4.1 Crop yields

When the yield rankings and the LSD groupings of the three crops were combined it can be seen that overall Plots 7, 8 and 9 were the lowest yielding plots (Table 3.40). The main explanation for these differences was the non-uniform distribution of water attributed to the use of a travelling irrigator and the prevalence for strong westerly winds that resulted in lower application rates in upwind plots (7,8 and 9) and higher application rates in down wind plots (4, 5 and 6). Plot 7 was slightly lower in elevation than other plots and might have been partially compensated for the lack of direct irrigation by runoff from the other plots.

Table 3.40. Plot yield rankings and Fishers LSD groupings of the three crops.

Plot Number	Strip Arrangement	Mean Broccoli Yield Rank	Broccoli LSD grouping	Mean Potato Yield Rank	Potato LSD grouping	Mean Onion Yield Rank	Onion LSD grouping	Average Yield Ranking
1	Onion Monoculture	-	-	-	-	1	a	**1.00**
2	BOPBOP	5	b	3	a	2	b	**3.33**
3	Potato Monoculture	-	-	2	a	-	-	**2.00**
4	POBPOB	3	a	1	a	4	b	**2.67**
5	OBPOBP	1	a	4	a	3	b	**2.67**
6	Broccoli Monoculture	2	a	-	-	-	-	**2.00**
7	BPOBPO	4	a	6	b	5	c	**5.00**
8	PBOPBO	6	bc	7	c	6	cd	**6.33**
9	OPBOPB	7	c	5	b	7	d	**6.33**

Key: P=Potatoes, O=Onions, B=Broccoli.

Plots with the same LSD grouping letter are not significantly different ($P > 0.05$)

To quantify the irrigation distribution, nine rain gauges were placed in a grid of the least (Plots 4, 5 and 6) and worst (Plots 7, 8 and 9) affected areas (Figure 3.4). Readings were taken after two successive irrigation events of approximately 35mm each. Table 3.41 demonstrates that the irrigation distribution varied considerably; with the middle plots (4, 5 and 6) receiving substantial amounts of water; the inside edges of Plots 7, 8 and 9 receiving adequate water; while the outside edges of Plots 7, 8 and 9 received substantially less water.

Figure 3.4. Rain gauge locations superimposed onto the experimental design.

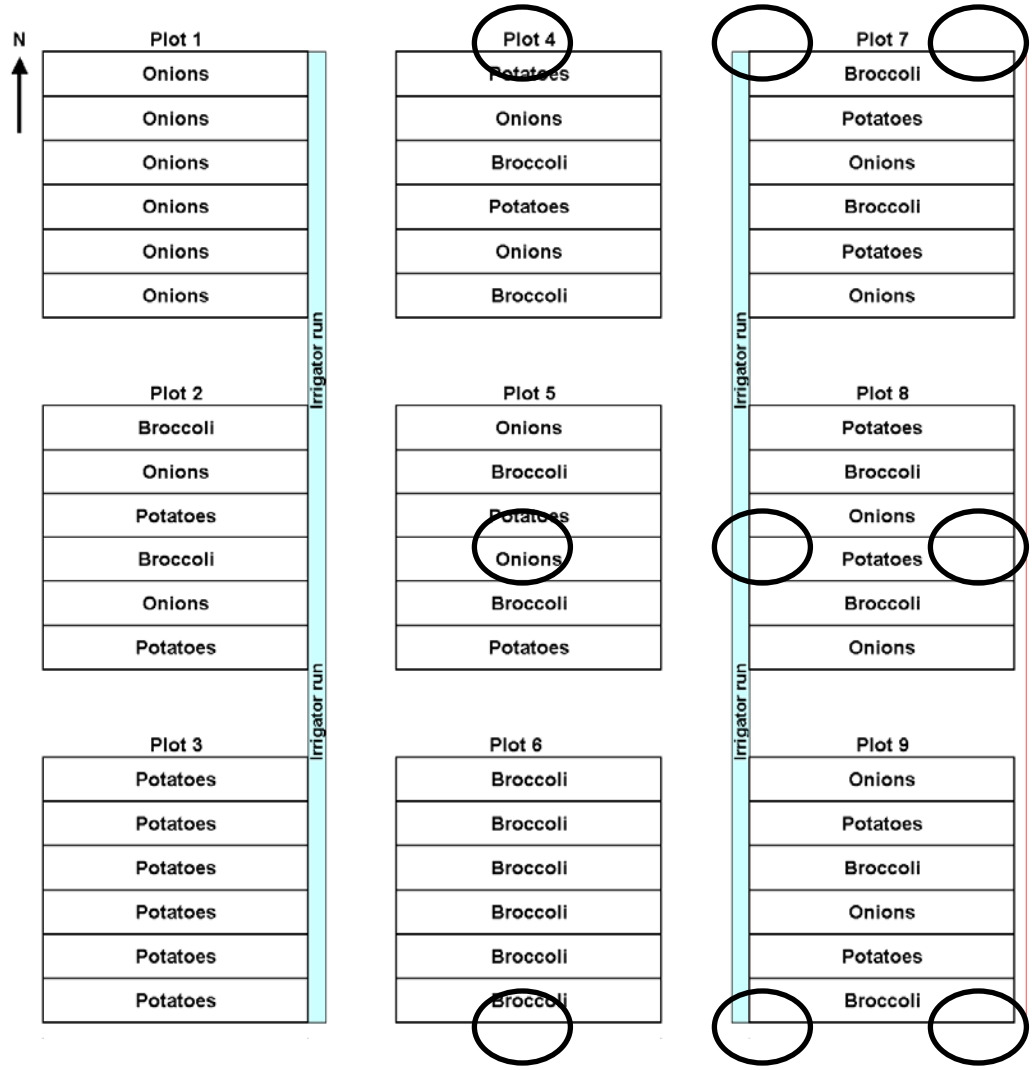


Table 3.41. Rain gauge measurements (mm) from 11/2/04 (#1) and 17/02/04 (#2) from the locations illustrated on Figure 3.4.

Plot 4 outside edge		**Plot 7 inside corner**		**Plot 7 outside corner**	
#1	**#2**	**#1**	**#2**	**#1**	**#2**
27	46	22	27	4	7
Plot 5 middle		**Plot 8 inside edge**		**Plot 8 outside edge**	
#1	**#2**	**#1**	**#2**	**#1**	**#2**
50	56	26	36	4	9
Plot 6 outside edge		**Plot 9 inside corner**		**Plot 9 outside corner**	
#1	**#2**	**#1**	**#2**	**#1**	**#2**
47	48	21	29	18	15

This lack of irrigation uniformity can be used to explain most of the reductions in yield from Plots 7, 8 and 9, and the yield variations across all the three crops studied. This effect substantially reduced the likelihood of detecting all but the strongest differences between the neighbouring plant configurations, which is especially evident in the onion neighbouring plant results, where a 10kg difference between the monoculture onions and all other neighbouring plant configurations was not statistically significant. The removal of the lowest yielding plots of each crop from the analyses eliminated the significant yield differences, largely due to a reduction in the degrees of freedom and therefore the statistical power of subsequent tests.

Despite the test of neighbouring plant configurations in onions being insignificant, the average weight of onions per plot indicated an onion production penalty in this strip cropping system due to having fewer onions in the larger size ranges. When compared to the other crops, onions are relatively poor competitors for resources. Onions require higher levels of phosphorous and potassium than other crops to facilitate uptake. These higher nutrient levels compensate for a shallow root system, low root densities and a lack of root hairs (Brewster 1994). There were deficiency symptoms evident (yellowing of leaves) on the strip edges, especially when onions were immediately adjacent to broccoli rows, indicating that onions were being out-competed for nutrients by the other crops (Picture 3.17.a). The broccoli and potato plants have greater leaf canopy plasticity and were able to extend leaves into the onion rows and out-compete onions for light (for example, Picture 3.17.b) limiting the bulking of onion bulbs and reducing the number of bulbs reaching the larger size ranges. It is possible that the potato and broccoli plants acted as aerial light partitions, which have been shown to reduce onion bulb dry matter accumulation (Peach *et al.* 2000).

Picture 3.17. (a). Yellowing of onions visible after the removal of neighbouring broccoli plants (left). (b). A broccoli leaf partially shading an onion plant (right).

The potato yield results indicated that there were no detectable differences in the performance of strip cropped potatoes or potatoes grown in the monoculture. Plot 8 was the lowest yielding plot and this was due to the greatest level of seed breakdown after planting.

Broccoli was the only crop to show significant differences between plants with different plant neighbours. The planned neighbouring plant contrasts indicated that when broccoli plants were grown immediately adjacent to potato rows or at the plot edges they produced heavier broccoli heads compared to monoculture broccoli, while broccoli grown next to onions produced lighter heads. Cabbages (*Brassica oleracea* var. *capita*) have been shown to compete more actively for above ground resources compared with below ground (Peach *et al.* 2000). The extra light available on the plot edges can explain the additional production in these treatments. The additional broccoli production on the potato edge rows may have been the result of temporal asynchronies of growth rates, as well as complementary canopy structures that can freely intertwine (illustrated by Picture 3.18), which effectively reduces the competition between potatoes and broccoli, facilitating higher broccoli yields (Santos *et al.* 2002). This complementarity means that neither crop dominated the association as potatoes have fast initial growth followed by a period of photoassimilate translocation to tubers, which does not actively compete with broccoli during their high resource demand phase, allowing greater exploitation of the available resources (Santos *et al.* 2002). Furthermore, faster growing short season crops like broccoli,

generally suffer less from competition for light (Keating and Carberry 1993) reducing the likelihood of higher yields on the strip edges. The lower yields of broccoli next to onions was most likely due to the close proximity of the onion rows (40cm from the broccoli plants as opposed to 80cm in the other treatments) and their high planting density, which increased competition for resources.

Picture 3.18. Complementarity of potato and broccoli leaf canopies on a strip edge with potatoes on the left and broccoli on the right.

3.4.2 Plant diseases

The analysis of the plant disease data was inhibited by the rapid onset of diseases, largely as a result of a planned absence of chemical disease protectants and an abnormal weather event in January. The weather event came in the form of a massive downpour of 95 mm on 28 January, followed by falls of 45mm and 16mm over the next two days. The initial rainfall on the 28 January was substantially higher than the previous single day January rainfall total since records began in 1889, with the next highest totals being 62mm on the 25/1/1991 and 50mm on the 20/1/1942. The 95mm helped the total rainfall in January to 161mm, which was also an historical record. Temperatures of between 20-24^{o}C for the

following week created a situation where fungal diseases rapidly spread in the onions and potatoes (broccoli had already been harvested).

While the rainfall event was the catalyst for the disease outbreaks, excess irrigation applied to the middle plots possibly contributed to the outbreak of downy mildew in the onions of Plot 5, by allowing the establishment of low levels of disease before January 28, which then rapidly multiplied in these ideal conditions. However, there was no evidence of differences in potato disease infection rates across the different neighbouring plant configurations due to the prevalence of seed borne diseases confounding the disease data.

Analysis of the data of the harvest rejection of broccoli heads due to white blister rust indicated that plot edges, onion edges and the middle strip rows had higher infection rates. This suggests that the disease was spread more easily to these zones. However, contrasting the effect of neighbouring plant rows on harvest rejection rates did not reveal any statistically significant results. Plot 7 was where the disease was first located and had significantly higher harvest rejection rates than the remaining plots. The removal of Plot 7 from the analysis did not result in any significant interactions or contrasts, but it did slightly increase the probability of a significant interaction for broccoli growing immediately adjacent to potatoes and the second row next to potatoes to below the P=0.1 level to P=0.0856 and P=0.0790 respectively.

3.4.3 *Plutella xylostella* (diamondback moth) distribution in broccoli

The analysis of the influence of the neighbouring plant interactions on the number of diamondback moths (*P. xylostella*) was approaching significance (P=0.0607), which can be explained by the low numbers of diamondback moths in the two rows adjacent to potato plants and the inner plot edge row, and the high numbers in the outer plot edge rows. The only contrast that was below P=0.1 was the contrast of both potato edge rows and the monoculture broccoli at P=0.0984. These two pieces of data, although not statistically significant, indicate that the effects of strip cropping broccoli and potatoes on the presence of diamondback moths might be worth further investigation.

3.5 Implications

Out of all the statistical tests performed there were very few significant results, all of which occurred between broccoli rows adjacent to potato rows. Despite the absence of a significant impact of strip cropping on potatoes, there is enough data to support further investigation of the interaction of broccoli and potatoes. The poor performance of onions in strip cropping and their negative impact on broccoli production, indicates that further experiments with onions are not warranted. Furthermore, the idea that volatiles produced by crops like onions have the potential to inhibit herbivorous insects (Uvah and Coaker 1984) has been recently refuted by Finch *et al.* (2003), bringing into question one of the major reasons for including onions in the experiment.

There is the possibility of substituting onions with another crop in the design. However, the study of two crops instead of three would reduce the management burden of subsequent trials allowing greater replication, more frequent sampling and theoretically a greater chance of revealing significant interactions. The results also indicate that any interactions are likely to occur at row edges between the crops and any interactions are unlikely to penetrate into any of the middle rows of the five-metre per strip design. Therefore there is no benefit to be derived in these vegetable crops from having more than two 1.65m strips, with the greatest chance of positive interactions coming from replications of single 1.65m strips where each row shares an edge row with another crop. Narrowing the experimental strip width would also allow greater replication in any subsequent designs using less experimental area, further reducing the management burden. A smaller experimental area would also facilitate the use of more accurate irrigation equipment reducing the chance of yield gradients due to lack of irrigation uniformity. Furthermore, if only broccoli and potatoes are used in further experiments, all the chemical weed control of the potato crop could be performed before the broccoli is transplanted, eliminating the need for specially designed spray equipment. However, further reducing each crop width to individual rows to make the system a true polyculture (both potatoes and broccoli in each 1.65m row) is impractical as the crops could not be planted and harvested using existing equipment and would unnecessarily complicate the cropping system.

There was little evidence of beneficial interactions reducing plant diseases or insect pests in the different crop configurations and no evidence of cross contamination. Downy mildew and white blister rust were not evenly distributed across the plots, which might indicate that disease spread from an initial source of infection was slowed by strip crops and the plot arrangements. The alternating pattern of the vegetable strips and plots might have acted as physical barriers between susceptible plants (Altieri and Liebman 1986; Potts 1990; Finckh and Mundt 1992) as the spread of many diseases is related to the density of susceptible plants per unit area (Potts 1990). However, the assessment of plant diseases in these crops and in this system was problematic due to the rapid onset of diseases and the ubiquitous nature of the pathogens. In general, the effects of diversification on diseases in plant diversity experiments are hard to predict due to complicated interactions between pathogen dispersal processes, infection efficiency and altered microclimates (Matson *et al.* 1997) and therefore are not a major focus in further experiments.

Chapter 4 The impacts of a rye cover crop and strip crops on insect pests of broccoli

4.1 Introduction

To investigate research questions identified in Chapter 2 and to build on the preliminary investigations discussed in Chapter 3, an additional layer of diversity, in the form of a cover crop, was added to field experiments conducted in the summers of 2004/2005 and 2005/2006. The results from the insect monitoring activities are discussed in this chapter and the agronomic results in Chapter 5. Although the agronomic interactions were important in understanding the differences between conventional practices, strip crops and cover crops, the insect responses observed in the 04/05 trial were more promising than the agronomic results. Therefore, a greater emphasis was placed on insect research in the 05/06 experiment.

4.2 Insect pests in Brassica cropping systems

The risk of insect damage and contamination of Brassica vegetable crops results in the frequent application of insecticides during the cropping season (Baker and Kovaliski 1999). However, the sole reliance on insecticides is ill advised due to the cost, consumer concerns and quality assurance issues in relation to chemical residues and the potential for the development of insecticide resistance (Hamilton *et al.* 2004). *Plutella xylostella* (Linnaeus) (Lepidoptera: Plutellidae) is the most destructive pest of Brassica crops throughout the world (Talekar and Shelton 1993) and is also the major pest in Australia (Endersby *et al.* 2006) where it is commonly known as the diamondback moth. This insect is of particular concern to farmers due to the development of multiple chemical resistance, which has led to insecticide control failures in Australia (Baker and Kovaliski 1999) and around the world (Zhao *et al.* 2002). This has led to the development of integrated pest management (IPM) and chemical rotation (resistance management) strategies in Australia (Baker 2004), the success of which is largely reliant on grower adherence to the guidelines. Various parasitic wasps have also been introduced to Australia to control *P. xylostella* (Furlong *et al.* 2004), but these are typically not effective as a stand alone control strategy (Keller and Baker

2003; Furlong *et al.* 2004). In some situations, like Tasmania, these biological control agents are often overwhelmed by large influxes of pests migrating from other breeding centres on favourable winds (Hill 1993). These factors suggest that alternative *P. xylostella* control strategies should be researched and developed. The use of crop diversification may be an alternative method of reducing the use of synthetic chemicals in Brassica cropping systems due to possible interference with host location, host acceptance and oviposition processes (Chapter 2). Two possible diversification strategies identified were strip cropping broccoli with potatoes and the use of a cover crop. The effectiveness of these strategies in reducing *P. xylostella* numbers in broccoli, when compared to the current practice of growing broccoli in a monoculture with extensively cultivated (bare) soil, will be the focus of this chapter. Two other pest species of lessor importance, the cabbage white butterfly *Pieris rapae* (L.)(Lepidoptera: Pieridae) and the cabbage aphid *Brevicoryne brassicae* (L.)(Homoptera: Aphididae) were also encountered in the broccoli plots and these will also be discussed.

4.3 Life histories of the major insect pests of Brassicas in Australia

4.3.1 Plutella xylostella

P. xylostella is a specialist herbivore of wild and cultivated plants of the Brassicaceae family with a cosmopolitan distribution (that is, the insect is found wherever Brassicas are cultivated). It is thought that *P. xylostella* originated in the Mediterranean where Brassica crops were first domesticated, although there is some evidence that the pest could have come from Africa (Kfir 1998). It is believed that *P. xylostella* had arrived in Australia by at least 1889 (Waterhouse and Sands 2001). The following life history of *P. xylostella* is based on the scientific description of this insect by Harcourt (1957).

Minute eggs, approximately 1.2mm in diameter, are typically laid on the leaves of the host plant. Each egg incubates for 4-7 days and then the newly hatched larva bores through the leaf epidermis and the first of four instars mines the spongy leaf mesophyll tissue from inside the leaf. The second instar moves to the surface and begins consuming all the leaf

tissue except the veins and the upper epidermis resulting in a “windowing” effect. The larva continues to develop gaining size through the third and fourth instar, after which the larva constructs a fine open-network cocoon in which to pupate. If the larva is disturbed at any stage it will wriggle rapidly backwards and often drop from the leaf on a fine silken thread where it will remain suspended until the disturbance has passed. The average duration of each instar is dependant on temperature, but usually between 4-6 days, with faster rates at higher temperatures. The pupation lasts 6-15 days, which is also dependant on temperature. The adult moth that emerges from the cocoon is nocturnal, becoming active one or two hours before sunset. They are weak flyers and are readily carried by the wind. Females mate only once, whereas males mate as many as three times. Oviposition begins shortly after dusk and continues until approximately midnight, reaching a peak two hours after dark. When the female locates and alights on a host plant, it crawls slowly over the leaf surface to a depression in the leaf along a midrib or vein. She then probes with her ovipositor briefly before depositing a single egg, which may or may not be appended with additional eggs.

The taxonomy of *P. xylostella* has been further described by Moriuti (1986). The fourth instar larva has an average length of 10mm and is often pale green in colour. Pupae are 5-6mm in length and are pinkish-white, pinkish-yellow, or sometimes green, which darkens to brown as the adult develops. The adult has a wing span of 12-15 mm.

Picture 4.1. A *P. xylostella* adult moth (left), pupa and 4th instar (middle) and three different instars (right), the middle and right pictures also illustrate “windowing” of the leaves due to larval feeding.

4.3.2 Pieris rapae

Pieris rapae is a cosmopolitan insect of European origin and a specialist herbivore of plants in the Brassicaceae family. The earliest sighting in Australia was reported in Melbourne in 1929 and it became established around the country by about 1937 (Waterhouse and Sands 2001).

P. rapae larvae develop from small yellowish bullet shaped eggs typically laid singly (Richards 1940). These eggs are approximately 1mm in height from the base to the apex and 0.45mm in diameter at its widest point, which is approximately a third of the distance from the base (Muggeridge 1942). The eggs are deposited and glued on either side of the host plant's leaf surface so that they stand vertically. When the larva first emerges it is very pale yellowish-green to white in appearance and approximately 1.5mm in length. It immediately eats the egg shell and then begins feeding on plant tissue and becomes green in colour (Muggeridge 1942). The larvae then progress through four other instars of approximately 9mm, 14mm, 20mm and 24mm in length before pupating in a chrysalid that measures approximately 19mm in length (Muggeridge 1942). Larvae survive at temperatures between 12^{o}C and 30^{o}C, with faster development rates at higher temperatures (Richards 1940).

Picture 4.2. A *P. rapae* adult (left) and *P. rapae* larvae (middle) *P. rapae* chrysalid.

4.3.3 Brevicoryne brassicae

B. brassicae is a cosmopolitan parasite of the Brassicaceae family and it originates from Europe (Waterhouse and Sands 2001). The following life cycle of the cabbage aphid *Brevicoryne brassicae* has been based on a description by Hughes (1963).

B. brassicae feeds on phloem from the leaves and stems of Brassica crops. Nymphs predominantly come from wingless females (apterate and degenerate) producing live young (vivipary) from unfertilised eggs (parthenogenesis). A single female can produce 30-50 nymphs at the rate of up to five a day, and at temperatures of 18^{o}C, this nymph can develop through its four nymphal instars and begin reproducing in seven days, meaning that numbers can increase rapidly. Variable proportions of these individuals develop wings in the adult stage (alate) and are well adapted for dispersal and colonisation of new plants. These are also typically female, parthenogenetic and viviparous. They also take slightly longer than the apteratae to develop and they produce fewer progeny (15-30) that are characteristically apterate. Low temperatures can lead to the development of alate males that result in a sexual cycle. However, this has been largely suppressed in Australia due to the ability of the insect to reproduce parthenogenetically throughout the year.

The adult apteratae are typically 2.1-2.7mm long, have a round shape, antennae less that half their body length and are covered with a characteristic white powder. The adult alatae are darker, have antennae as long as their bodies and transparent wings twice as long as their bodies.

Picture 4.3. An alate *B. brassicae* adult with nymphs (left), an aphid colony with a *Diaeretiella rapae* wasp (middle), and an aphid colony with parasitised (brown) mummies (right).

4.4 Insect pest host location

Host location and oviposition are crucial steps in the life cycle of numerous insects. Immature stages of *P. xylostella* and *P. rapae* are relatively immobile and dependent on the ability of the adult female to choose a suitable host plant (Renwick and Chew 1994) as the larvae can only grow and survive on a limited number of plant species belonging to a single

family (Hern *et al.* 1996). Host location by aphids can be described as a passive process. The alate adults are relatively poor fliers that are carried by the wind for long distances (Compton 2002), primarily because they can make no progress against winds of more than 0.6 ms^{-1} (Hughes 1963). Even for insects like *B. brassicae* with a narrow host range, their vision is primarily used to distinguish plants from the sky (Kennedy *et al.* 1961) and they have no specific attraction to the host plant over more than a metre distant and will alight and take off from host and non-host alike resulting in the mortality of upwards of 99% of individuals (Hughes 1963). It is only a minutely higher probability that they will remain on a host plant compared to a non-host plant that facilitates colonisation (Hughes 1963). There is evidence from electro-physiological experiments that *B. brassicae* respond positively to host plant volatiles (Nottingham *et al.* 1991), however these are unlikely to provide directional information (Finch and Collier 2000) but rather act on host plant acceptance behaviour after landing has occurred (Compton 2002).

Host location in insects is not necessarily a complicated process. Finch and Collier (2003) report that phytophagous insects are so successful at locating plants because they have "kept things simple". They summarise host location as being made up of three basic steps:-

1. Chemical stimuli (plant odours) indicate when to land.
2. Visual stimuli (colour and contrast) indicate where to land.
3. Touch and taste indicate host suitability and hence whether to stay or fly away.

To reduce colonisation and plant damage, a cropping system has to interfere with one of these steps. The simplest to alter in a cropping system is the visual stimuli present (where vision in insects is defined as the ability to perceive spatial patterns [Prokopy and Owens 1983]). This is also arguably the most important as the visual perception of plant colour and shape are "undoubtedly" the dominant sensory cues for moths and butterflies searching for host plants (Renwick and Chew 1994). The current practice of "clean" cultivation of crops, with a zero tolerance of non-crop plants, like weeds and cover crops, ensures that crop plants are exposed to the maximum pest pressure due to the ease of host location when there is a high visual contrast between plants and a bare soil background (Finch and Collier 2000). A reduction in the contrast between the soil and the host plants by the use of

background vegetation may lead to a reduction in pest pressure. For example, Mangan *et al.* (1995) and Masiunas *et al.* (1997) found fewer insect pests in cabbages grown with cover crops including cereal rye (*Secale cereale*) when compared to conventional tillage (a bare soil background).

Despite decades of field studies there is no reliable, generalised strategy for deploying diversity into crop fields to manage insect pests, probably due to experimental differences in insect behaviour; plant physiology and the scale of experiments (Andow 1991; Banks and Ekbom 1999); inadequate research methods (Smith and McSorley 2000); and the perpetuation of "myths and untested assumptions" (Finch and Collier 2000) such as volatile chemicals released from companion crops "masking" the presence of a host plant (Finch *et al.* 2003). The spatial arrangement and density of planting may also be a factor because at higher plant densities, insects locate hosts more readily when uniformly dispersed than when the plants are clumped (Hern *et al.* 1996). Furthermore, theoretical mechanisms accounting for herbivore/plant/predator interactions in plant mixtures have not been thoroughly evaluated (Hooks and Johnson 2003). These issues have contributed to ambiguities meaning that few robust generalisations can be made about the effects of infield plant diversity on insect pest densities.

For crop diversification strategies to be successful, Hooks and Johnson (2003) recommended that attention should be paid to:

1. Defining ways to suppress Brassica pests without significantly affecting yield.
2. Determining how mixed cropping systems impact population dynamics and host finding behaviour.
3. Discovering methods to make mixed Brassica systems more economically feasible and compatible with current conventional farming systems.
4. Determining how mixed cropping systems can be effectively combined with other pest management practices.

In addition, Schellhorn and Sork (1997) report that the plant mixtures chosen for diversification strategies need to be of relatively unrelated species, as mixtures of plants from one family can increase the number of specialist herbivores.

Combining a fragmented field, using strip cropping, with a visually diverse background through the use of a cover crop, could conceivably progress some of these issues and has the potential to increase the effects of either pest management strategy on host location in an additive fashion, without affecting yield. Furthermore using tractor width strips facilitates field management with minimal change to current practices.

4.5 Methodology

The main outcomes of the Preliminary Investigations detailed in Chapter 3 were that onions were unsuitable for further experimentation in a strip cropping system and that any zone of interaction was likely to occur on the rows immediately adjacent to an alternative crop. The removal of onions as a focus crop meant that the size of the experiment area could be reduced and the replication increased. After incorporating these factors in the design, the 04/05 trial investigated the impact of four cropping systems on the abundance of insect pests. The cropping systems were based on two factors; the first was either a strip crop utilising broccoli (*Brassica oleracea* var. *italica*) host plants with non-host potatoes (*Solanum tuberosum* cv. Russet Burbank) or a broccoli monoculture; the second factor was using either conventional tillage or a cover crop. The 05/06 trial included another strip cropping option in the form of dead standing rye strips, and investigated if the effects from 04/05 were caused by interference with oviposition, differential egg survival or changes in the host quality of the plants in the different treatments.

To avoid repetition, this chapter describes the site and experimental methods that were common to the experiments in this chapter and Chapter 5. Materials and methods specific to each chapter are described in the respective chapters.

4.5.1 Choice of the cover crop

One option for increasing diversity in a cropping system is via the addition of a cover crop or a living mulch (vertical diversity, see Chapter 2). The choice of the cover crop or living mulch had to take into account the initial goals of this thesis outlined in the Introduction, in

that the system with the potential to reduce insect pressure (and potentially reduce chemical use) should not significantly reduce yield and consequently the income of farmers.

Competition with the harvested crop for light, nutrients and water and the subsequent reduction in yield is a major problem with living mulches (Root 1973; Horn 1987; Lotz *et al.* 1997; Theunissen 1997), which is not effectively suppressed with mowing (Brandsæter *et al.* 1998). Furthermore, living mulches are not always effective at reducing weed pressure (Brandsæter *et al.* 1998) unless weed pressure is low (Infante and Morse 1996). To minimise competition for light, nutrients or water, the ground cover crop should be killed prior to planting the component of the system to be harvested. This "cover crop" should also be dense, uniformly distributed and managed so that it that covers and shades the soil in order to suppress weeds (Morse 1998). In transplanted cabbages, a cereal rye (*Secale cereale* L.) cover crop killed with glyphosate has been shown to assist in controlling insect pests while reducing weed populations (Bottenberg *et al.* 1997). Rye cover crops have also been shown to reduce crop yields (Mwaja *et al.* 1996; Bottenberg *et al.* 1997). However, the crops in these studies were harvested on a single day, potentially biasing the results as rye cover crops have been shown to delay harvests by up to three weeks when compared to crops grown in cultivated soil (Borowy 2004), and would appear to have yielded less. Rye has the added benefit of being easily killed with a single glyphosate application and/or rolling (Ashford and Reeves 2003). Furthermore, of 14 cover crops screened by Nelson *et al.* (1991), which included grasses, legumes and cereals, rye had the greatest percentage of ground cover and was the most suppressive of weeds. Masiunas *et al.* (1997) found that dead rye was the most promising mulch for cabbage. Similar rye cover crops have also been trialled previously in Tasmania (Young and Hingston 1993) and on potatoes (Wallace and Bellinder 1990; Bellinder *et al.* 1996). For these reasons a cereal rye cover crop was chosen for inclusion in the following experiments.

4.5.2 Field trial designs

Separate field experiments were conducted in the summers of 2004/2005 and 2005/2006 at the Forthside Research Station (as per Chapter 3). The 04/05 experiment consisted of three replications of eight plots in a randomised block. Each plot was 10m x 10m with a 5m

separation between plots with bare soil on the sides and grass at each end (Figure 4.1). The first factor of the experimental design was a continuation of the Preliminary Investigations of 03/04 (Chapter 3), with either broccoli (*Brassica oleracea* var. *italica* cv. Green Belt) strip cropped with potatoes (*Solanum tuberosum* cv. Russet Burbank), or broccoli grown in a monoculture. The second factor constituted the additional layer of diversity, with broccoli either transplanted into a chemically killed and mechanically rolled rye (*Secale cereale*) cover crop or into conventionally tilled soil. To maintain balanced numbers of broccoli plants in each treatment, there were two strip cropping plots to each monoculture plot per replication (Picture 4.4). Ignoring the potato monocultures, the treatments were grouped as follows:

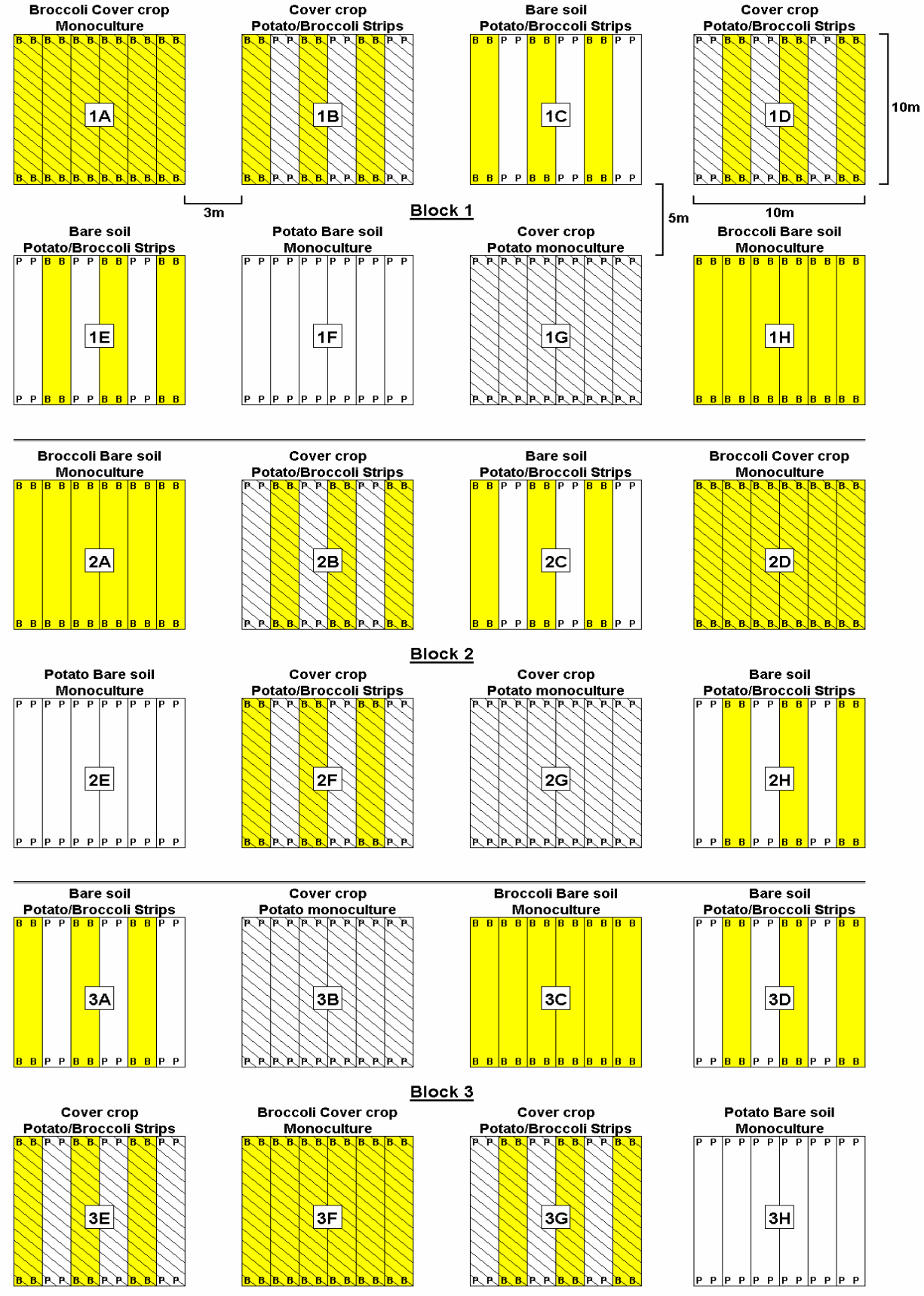
1. Broccoli monoculture planted in a rye cover crop (Cover crop/Monoculture).
2. Broccoli and potato strip crop planted into a rye cover crop (Cover crop/Potato strips) in two combinations.
3. Broccoli monoculture planted into bare soil (Bare soil/Monoculture).
4. Broccoli and potato strip crop planted into bare soil (Bare soil/Potato strips) in tow combinations.

An example ANOVA table is presented as an appendix. A randomly allocated subplot treatment for half of each strip consisted of green turf paint applied in order to determine the effects of artificially altering background colour on insect colonisation of broccoli, especially in the cover crop treatments.

To increase statistical power and remove possible site-specific sources of error, the 05/06 experiment consisted of six replications of a 3 x 2 factorial design in a latin square arrangement (Figure 4.2). Each plot was 9m x 9m with 3m of bare soil separating plots. There were a total of 27 broccoli plants in each 9m row. Introducing a further layer of diversity by using broccoli cultivar mixtures (within crop diversity) in the 05/06 experiment, as described in Literature Review (Chapter 2), was ruled out due to design difficulties stemming from ensuring that each variety was represented in both mixtures and monocultures as well as stripping and cover cropping treatments. The turf paint treatment subplot was removed from the 05/06 experiment due to the absence of any significant

interactions in the 04/05 trial. Another side-by-side diversity option was included in the 05/06 experiment with the addition of rye strips that were killed with glyphosate and left

Figure 4.1. Experimental design 04/05. P=potato, B=broccoli and diagonal lines=cover crop.



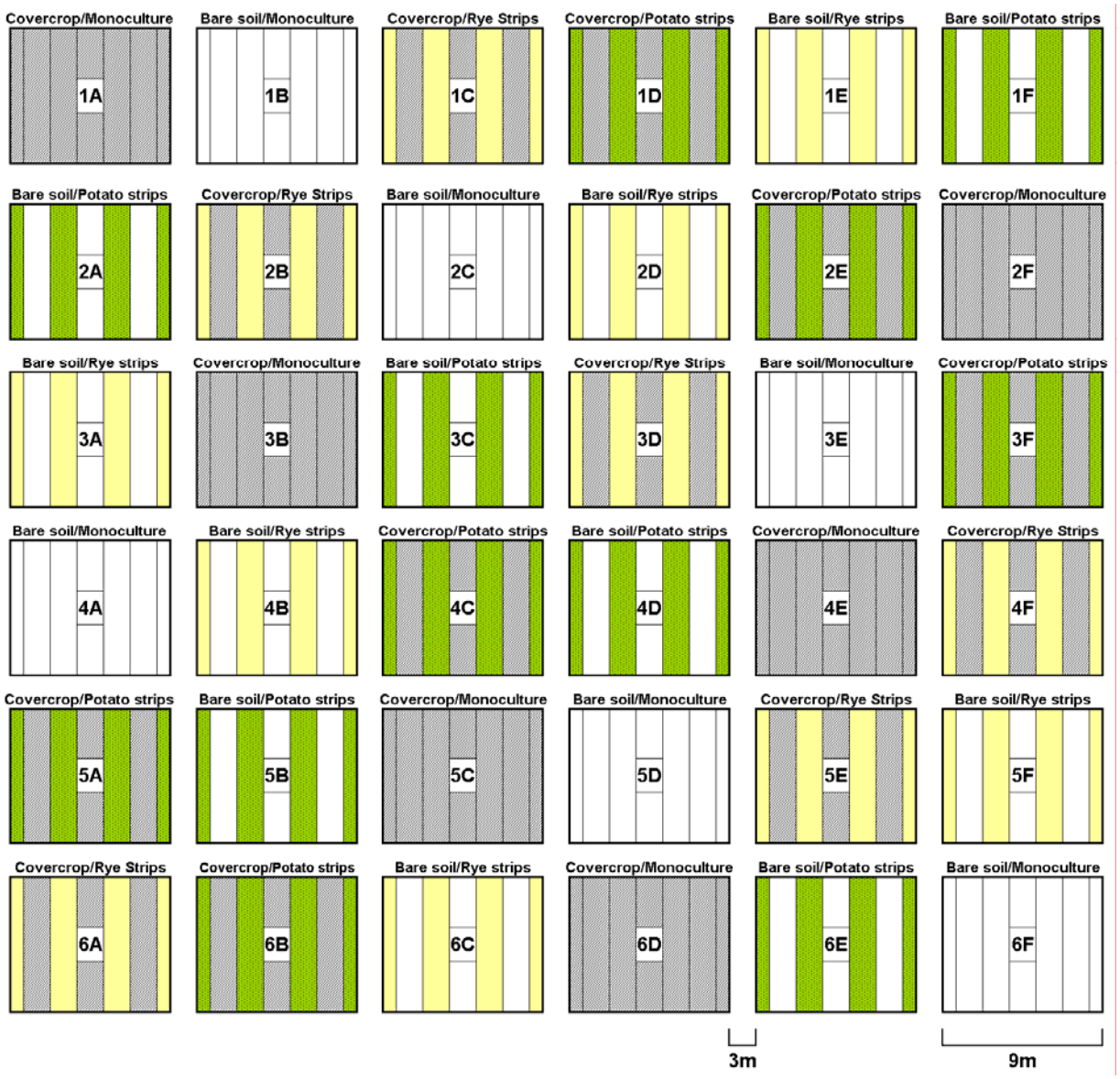
Picture 4.4. Treatments for the 04/05 experiment (clockwise from top left) Cover crop/Monoculture . Cover crop/Potato strips, Bare soil/Monoculture, Bare Soil/Potato strips.

standing *in situ* (Picture 4.5). The standing rye strips were included to determine if there were any sheltering effects on the developing broccoli and to determine if the simple presence of rye in a plot had any effects on the insect pests. Therefore the same factors as 04/05 were used in the 05/06 experiment with the addition of standing (killed) rye. In summary the six individual treatments for the 05/06 trial were:

1. Broccoli monoculture planted in a rye cover crop (Cover crop/Monoculture).
2. Broccoli planted into a rye cover crop with adjacent standing dead rye strips (Cover crop/Rye strips)
3. Broccoli planted into a rye cover crop with adjacent potato strips (Cover crop/Potato strips).
4. Broccoli monoculture planted into bare soil (Bare soil/Monoculture).
5. Broccoli planted into bare soil with adjacent standing dead rye strips (Bare soil/Rye strips)
6. Broccoli planted into bare soul and adjacent to potato strips (Bare soil/Potato strips)

An example ANOVA table is presented as an appendix.

Figure 4.2. Experimental design 05/06. Where green=potato strips, yellow=rye strips, grey=cover crop broccoli and clear=bare soil broccoli.



Picture 4.5. Additional treatments for the 05/06 experiment: Bare soil/Rye strips (left) Cover crop/Rye strips (right). Note that the photos were not taken on the same day.

4.5.3 Trial establishment

The cereal rye for the cover crop was sown on 7 September 04 and 21 September 05 at the common rate of 100kg/ha with 50kg/ha of fertiliser (14N:16P:11K). Potatoes were planted on 4 November 04 and 2 November 05. The cover crop for both experiments, and the standing rye strips in the 05/06 experiment, were sprayed and killed with glyphosate (720g ai/ha), on the 26 November 04 and 13 December 05.

For the 04/05 trial, the cover crop was mechanically rolled and fertiliser was predrilled in 80cm rows on 2 December 04. The following day, broccoli was transplanted by hand into the 80cm wide row marks, with an intra-row spacing of 30cm. Green turf paint (Lawn Greenger®, Becker and Underwood Inc., Underwood, Indiana) was applied on 6 December 04 to half of each broccoli plot, including bare soil treatments, at the rate of 6.5L/ha diluted into 130L/ha. For the 05/06 experiment on 19 December 05, the cover crop was mechanically rolled, fertiliser was drilled and the broccoli Speedlings were transplanted in 80cm rows, 30cm apart in one pass using a prototype planter developed by the author (discussed in Chapter 6). On both occasions fertiliser (13N:15P:13K:1S) was applied at the rate of 500kg/ha.

For both trials an insecticide was applied (spinosad 0.128kg ai/ha) at 48 days after transplanting (DAT) (04/05) and 51 DAT (05/06) to prevent the confounding of yield data by insect damage and to enable the later sale of broccoli for cost recovery.

4.5.4 In-field insect sampling 04/05

To describe the insect abundance in each cropping system of the 04/05 trial and to determine if there were any treatment differences in these abundances, 60 randomly selected broccoli plants per plot (excluding the outside edge rows) were non-destructively scouted each week. A new randomisation was prepared before each sampling date. This monitoring commenced at 12 DAT and continued for five weeks until 41 DAT. For *P. xylostella* and *P. rapae*, larvae and pupae numbers were recorded, and in the case of *B. brassicae*, the presence or absence of colonies (groups 10 or more individuals) and parasitised mummies were recorded.

In the 04/05 experiment, immediately prior to the application of insecticide at 48 DAT, 20 *P. xylostella* fourth instar larvae were removed from each treatment for each of the three replications. To determine if there were differences in the presence of internal parasitoids across the treatments these *P. xylostella* larvae were dissected under a microscope using the method described by Hamilton *et al.* (2004).

4.5.5 Establishing a *P. xylostella* laboratory population

To perform more complex experiments on *P. xylostella* in 05/06, a readily available supply of adult moths, eggs and larvae needed to be established. Therefore, a laboratory population of moths was established on 31 October 2005 using 300 *P. xylostella* pupae sourced from Dr. Nancy Endersby of the Victorian Department of Primary Industry at Knoxfield. The pupae were placed in a 1.7m x 1.2m x 1.2m cage (width x depth x height) in the glasshouse at the University of Tasmania Cradle Coast Campus, Burnie (E405830, N5453790). The moths that emerged were maintained on a diet of honey and were exposed to natural light and a constant temperature of between 17^{o}C and 20^{o}C. To increase numbers these moths were allowed to oviposit on broccoli plantlets (cv. Marathon), which were then moved to an adjacent cage of the same dimensions for the larvae to develop. Pupae from the larvae cage were regularly removed and placed in the adult moth cage.

To enable the collection of accurate *P. xylostella* data, three training tasks were then undertaken using the laboratory population. The first task was to establish a 'search image' for *P. xylostella* eggs for when plants from the 05/06 field experiments were dissected. The search image was developed through examinations of *P. xylostella* eggs oviposited by moths in the laboratory using jeweller's glasses. The second training task was to visually determine the differences between the instars so that accurate population data could be collected when plants from the 05/06 experiments were dissected. This was achieved by careful monitoring of the development of the first new *P. xylostella* generation of the laboratory population. The third activity was to accurately sex *P. xylostella* adults in order to be able to place adult females into cages placed in field the for monitoring egg survival rates. Using taxonomic notes from Moriuti (1986), 40 adults were removed from the cage,

sexed and placed in small plastic containers with a small broccoli leaf. All moths sexed as females laid eggs, while none of those classed as males laid eggs.

4.5.6 Destructive sampling 05/06

To gather more accurate *P. xylostella* and *P. rapae* egg, larvae and pupae data and more accurate alate, apterate and parasitised *B. brassicae* data in 05/06, three broccoli plants from each trial plot were destructively sampled and dissected each week. This sampling commenced at 14 DAT and continued for five weeks until 44 DAT. At each sampling date, one plant from each of the three strips per plot was cut at the soil level with a pair of secateurs and placed in a large labelled clear plastic bag. The sampled plants were then taken to a nearby workspace and inspected under lights using jeweller's glasses (Picture 4.6). In the case of *P. xylostella*, the numbers of eggs, each of the four instars and pupae were recorded. All pupae were collected and placed in labelled plastic containers and allowed to continue pupation. These data were used to determine if there were differences in colonisation (number of eggs), survival (numbers of different instars and pupae) and parasitism (*P. xylostella* moth or parasitoid emergence from pupae) between treatments. For *P. rapae*, the presence of eggs, different instars and pupae were recorded. These data were also used to determine if there were differences between colonisation (number of eggs) and survival (number of different instars and pupae) across the treatments. For *B. brassicae*, the number of alate adults was recorded along with the presence or absence of colonies of 10 or more individuals and parasitised mummies. These data were used to determine if there were differences between colonisation (number of alate aphids), rates of infestation (presence/absence of colonies) and rates of parasitism (presence/absence of parasitised aphid mummies) across treatments.

Picture 4.6. The author inspecting broccoli plants using jewellers glasses.

As one plant from each strip was to be removed each week for seven weeks, it was important to minimise the potential confounding effects of the removal, that is, access to additional resources by the remaining plants and/or potential differences in insect colonisation brought on by gaps in the rows. Therefore, a structured sampling plan was devised to minimise these potential problems (Figure 4.3).

There were 12 “selectable” plants in each sampling strip. These “selectable” plants were randomly allocated to an experimental procedure, that is: seven plants for the destructive harvest; two plants for the exclusion cage and the egg placement experiments; and the remaining three plants for the final harvest to assess yield and quality (Chapter 5). The starting position was also randomised, that is, whether to start the numbering on the left hand side or the right hand side. Starting at the “top” position looking down the rows to the “bottom”, the example in the diagram below starts on the left side. The opposite rows would highlighted if “right” had been the starting position.

Figure 4.3. Sampling schematic for 05/06 experiment, where the numbers indicate a broccoli plant and the highlighted plants were “selectable”.

	Border Row																										
Top	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
	Border Row																										

Bottom

The total number of plants from each sample was 108. The large number of plants to be assessed and the time required to search for insect eggs, larvae and pupae meant that the third and fourth samples were taken over two days and the fifth sample was taken over 3 days. The sixth and seventh samples (52 and 59 DAT) were completed in a day, as the insect data was no longer collected. When the sampling was split over two different days the plants were destructively sampled in Blocks starting with Blocks 1, 2 and 3 on the first day and Blocks 4, 5 and 6 on following day. When the samples were taken over three days, Blocks 1 and 2 were taken on the first day, Blocks 3 and 4 on the second day and Blocks 5 and 6 on the third day. This process was important to reduce sampling fatigue and was taken into account in the model statement of the statistical analysis.

4.5.7 Vacuum sampling for *P. xylostella* adults 05/06

A vacuum sample of *P. xylostella* moths was taken at dusk 4 DAT to determine if there were differences in the number of male and female adults across the different treatments in the 05/06 experiment and to determine if this related to the number of eggs present in the treatments. However, difficulties encountered in operating the vacuum sampler in the cover crops due to the small size of the transplants and interference from the rye meant that vacuum sampling had to be delayed until 36 DAT when the broccoli plants had grown above the rye cover crop. Further vacuum samples were taken 44 and 50 DAT. The sampling regime consisted of two randomly selected nine-metre runs per plot at a controlled walking pace. As the sampling process took approximately 1 hour, each six-plot block was sampled together in order to determine if there were any differences in the number of moths due to sampling time. The sample bags were placed in a freezer overnight and the moths were counted and sexed the next morning using a stereo-microscope.

4.5.8 *P. xylostella* egg predation experiments 05/06

To determine if there were any differences between egg predation rates in the different treatments in 05/06, two experiments were undertaken. The first experiment involved monitoring the survival and predation of sentinel eggs oviposited by female moths taken from the laboratory population and placed in cages surrounding broccoli plants in the field. For the second experiment, eggs oviposited by the laboratory population were manually placed in the field and monitored for survival and predation.

For both experiments, round exclusion cages 30cm in diameter were made up from a roll of 90cm high mesh with wires spaced at 10cm x 10 cm. For the first experiment, each cage was covered with a white lycra netting sock, while for the second experiment each cage remained uncovered. On 17 January 06 two plants were randomly selected from each plot using the structured sampling plan discussed in Section 4.5.6. One plant per plot was assigned to the first experiment and the other was assigned to the second experiment.

For the first experiment each plant was wiped down with a damp cloth and inspected to ensure that all insects, eggs, larvae and pupae were removed. An exclusion cage (Picture 4.7.a) was then placed around each plant and secured in place with four tent pegs. On 23 January 06, 144 one day old female moths from the laboratory population were exposed to males for four days and then placed in small plastic containers. These females were assumed to be gravid. Four females were placed inside the exclusion cage surrounding each of the first randomly selected plants by cutting a small hole in the netting at the top of the cage, dropping in their opened container and then stapling the hole shut (Picture 4.8). After 48 hours, on 25 January, each of the covered cages was removed and the plants were scouted for eggs. The total number of eggs per plant was tallied then each egg was circled using a black permanent felt tip pen.

Each of the plants allocated to the second experiment was wiped down on 17 January 06 to remove eggs and larvae, then an uncovered cage was placed around it (Picture 4.7.b). Five eggs obtained from the *P. xylostella* laboratory population were placed on each of these plants on 23 January 06. As the eggs were not sticky, to prevent loss they were placed on horizontal parts of broccoli leaves where the plant was braced against the surrounding cage. The eggs were then circled with the black permanent marker. On 31 January 06, each egg from both experiments was assessed as being hatched, attacked or missing. The experiment was not irrigated from the 23 January until 31 January to reduce the likelihood of water related mortality described by Talekar *et al.* (1986).

Picture 4.7. (a). Exclusion cage with netting before placement (left). (b). An uncovered cage surrounding a broccoli plant (right).

Picture 4.8. Placing moths in exclusion cages, with the moth containers and equipment (left) and re-sealing the entrance hole (right).

4.5.9 Laboratory population oviposition experiment

To determine if there were any oviposition preferences or inhibitions due to possible treatments effects on the intrinsic host quality or desirability of the broccoli plants, an oviposition experiment was conducted using the adult *P. xylostella* laboratory population. On 9 February 06, three broccoli leaves were cut from each treatment by pressing and gently twisting a petri dish against the underside of a cleaned leaf with a chopping board placed on the opposite side. Each petri dish then contained a whole, topside up, round section of a broccoli leaf. The leaf samples were immediately taken from the field and placed in the centre of the adult moth cage for 24 hours in a randomised arrangement with

three replications (in three trays). A stereo-microscope was then used to count the eggs on each leaf. The procedure was repeated on 14 and 21 February 06.

4.5.10 Semi commercial cover crop experiment 05/06

To determine if the cover crop results from the 04/05 experiment were valid at scales greater than the plot size of $10m^2$, with the view of commercial implementation, a semi-commercial planting of one hectare of broccoli was established on a farm at Gawler (E 429220, N 5440190) on Tasmania's northwest coast. This location was 15km west of Forthside Research Station and in a similar environment (climate and soil). The experimental area was 50m wide and 200m long and divided into four plot pairs, each plot being 25m x 50m. One plot in each pair was randomly designated to have either a cover crop or to be prepared using conventional tillage (that is, bare soil). The rye cover crop was sown on 17 August 05 at a rate of 100kg/ha without fertiliser. The cover crop was sprayed and killed on 15 November 05 using glyphosate (720g ai/ha). Due to time constraints brought on by developmental problems with the one-pass roller/ transplanter, only half the area was planted with broccoli on 5 December, making each plot 12.5m wide and 50m long. Again time constraints, in this instance associated with the management and sampling regime of the Forthside trial, meant that for this experiment 15 randomly selected plants from each plot were sampled once for the presence of *P. xylostella* eggs and larvae, *P. rapae* larvae and *B. brassicae* colonies on 28 December (23 DAT). The trial was terminated on 23 January.

4.5.11 Data analysis 04/05

The *P. rapae* and *P. xylostella* larvae and pupae counts from the 04/05 experiment were analysed using a one-way analysis of variance (ANOVA) (Proc GLM, SAS Institute, Cary, NC) for each sampling date. The mean counts from each plot were used as the response variables, while the three replications (blocks) and the four treatments (treatments) were the predictor variables. Treatment means were separated using Fisher's least significant difference (LSD) and data were log+1 transformed when necessary to conform to the assumptions of the ANOVA procedure. However, only non-transformed data were reported in the figures and tables.

The *B. brassicae* colony and parasitism data from the 04/05 experiment were based on the proportion of plants infested. Therefore the data were arcsine square root transformed prior to using the ANOVA procedure. These proportions were used as the response variables, while the predictor variables were also the blocks and treatments.

To determine the effects of different treatments, pairwise contrasts were also planned for all the insect data. These contrasts were performed using the ANOVA model so that the results from the monoculture plots were compared to the results from the strip cropping plots; and the results of the cover crop plots were compared to the bare soil plots.
The pairwise contrasts for 04/05 can be summarised as:

1. Cover crop vs. Bare soil
2. Strip crop vs. Monoculture

An example ANOVA table is presented as an appendix.

4.5.12 Data analysis 05/06

The *P. rapae* and *P. xylostella* egg, combined larvae and pupae counts and the *P. xylostella* vacuum sampling data from the 05/06 experiment were analysed using a one-way ANOVA (Proc GLM, SAS Institute, Cary, NC) for each sampling date. The mean counts from each plot were used as the response variables, while the six columns (block) and the six rows (row) of the Latin square design; and the six treatments (treatment) were the predictor variables.

For the oviposition preference experiment, an ANOVA was also used to analyse the data. The number of eggs oviposited were used as the response variable while each tray, treatment and replication were used as the predictor variables.

For all ANOVA analyses, treatment means were separated using Fisher's least significant difference (LSD) and data were log+1 transformed when necessary to conform to the assumptions of the ANOVA procedure. However, only non-transformed data were reported in the figures and tables.

To determine the effects of different treatments, pairwise contrasts were planned for the *P. rapae* egg and larvae data; and for *P. xylostella* egg, larvae, laboratory population oviposition preference and vacuum sampling data. These contrasts were performed using the ANOVA model so that the results from the monoculture plots were compared to the results from the strip cropping plots (both rye strips and potato strips); the results from the cover crop plots were compared to the bare soil plots results; and the bare soil monoculture plots results were compare to the two bare soil strip cropping plots (both rye strips and potato strips).

The pairwise contrasts for 05/06 can be summarised as:

1. Cover crop vs. Bare soil
2. Strip crop vs. Monoculture
3. Bare soil strip crops vs. Bare soil monoculture

An example ANOVA table is presented as an appendix.

The *B. brassicae* data from the 05/06 experiment were based on the presence or absence of colonies and parasitised aphids. The use of the presence/absence sampling regime and a low effective sample size (three instances per plot) meant that a logistic regression with a dichotomous response was the appropriate analysis using Proc LOGISTIC in a SAS model (Stokes *et al.* 2000) in a process summarised by Equation 4.1. The predictor variables were block, row, treatment and sampling date. The odds ratios for each treatment, with respect to the reference level, correspond to the exponential of the logistic regression estimate for that treatment.

Equation 4.1. The logistic regression predictive probability for a treatment is given by the formula where t_i is treatment i; c is the regression intercept coefficient; and β_i is the regression coefficient for treatment i.

$$Prob(t_i) = \frac{\exp(c+\beta_i)}{1+\exp(c+\beta_i)}$$

For the exclusion cage experiment the number of eggs oviposited were analysed using a logistic regression with a polytomous response (Proc LOGISTIC) with three possible outcomes, where the responses were that the eggs could have hatched, been predated or were missing. This process is summarised by Equation 4.2. As these responses had no inherent ordering they were classed as nominal responses (Stokes *et al.* 2000) so the logistic regression was performed using generalised logits. The predictor variables were block, row, treatment and sampling date (date). The odds ratios for each treatment, with respect to the reference level, also correspond to the exponential of the logistic regression estimate for that treatment.

Equation 4.2. The polytomous logistic regression predictive probability for a particular outcome for a treatment is given by the formula where o_j is outcome j (hatched, missing, or attacked); t_i is treatment i; c_j is the regression intercept for outcome j; β_{ij} is the regression coefficient for outcome i with treatment j; and k is the index of all outcomes (hatched, missing, or attacked).

$$Prob(o_j|t_i) = \frac{\exp(c_j + \beta_{ij})}{\sum_k \exp(c_k + \beta_{ik})}$$

4.6 Results

Over the course of the 04/05 and 05/06 seasons, the insect herbivores encountered in large numbers on broccoli plants were two Lepidopteran pests, *Plutella xylostella* (diamondback moth) and *Pieris rapae* (cabbage white butterfly), and one Hemipteran pest, *Brevicoryne brassicae* (cabbage aphid). The results from each of these insects will be presented separately. All analyses of the differences between the split plots in 04/05 with and without green turf paint were insignificant (data not presented), therefore the insect results were presented as total plot means and the turf paint treatment was not included in the 05/06 experiment.

4.6.1 Meteorological data

Average meteorological data for temperature and rainfall for each of the trial seasons is presented in Table 4.1. The biggest difference between the two seasons was the much higher rainfall totals that occurred in the early part of the 05/06 season. As the experiments were irrigated to prevent soil moisture from being a limiting factor, this would have had little effect on plant performance in the different years. The main potential differences stemming from the additional rainfall, might have been a reduction in local population of *P. xylostella* in the 05/06 season prior to commencement of the experiment, as rainfall is a significant mortality factor for this insect (Talekar and Shelton 1993). However, the numbers of *P. xylostella* in the 05/06 experiment were on average the same or higher than in the 04/05 experiment.

Table 4.1. Mean monthly meteorological data for Forthside from September to March in 04/05 and 05/06 with long term averages in brackets.

Month - Year	Min. Temp. (degC)		Max. Temp. (degC)		Rainfall Total (mm)	
September-04	5.7	(4.9)	14.2	(13.3)	30.4	(98.3)
October-04	6.9	(6.2)	15.8	(15.40)	52.4	(84.9)
November-04	9.0	(8.1)	17.5	(17.1)	84.8	(69.5)
December-04	10.6	(9.6)	20.4	(18.9)	35.8	(67.5)
January-05	11.7	(11.0)	21.0	(20.6)	14.8	(54.4)
February-05	12.2	(11.6)	21.7	(21.0)	0.4	(45.8)
March-05	9.4	(10.4)	19.6	(19.8)	3.8	(55.5)
September-05	5.2	(4.9)	13.6	(13.3)	117.2	(98.3)
October-05	8.8	(6.2)	15.6	(15.4)	225.0	(84.9)
November-05	9.7	(8.1)	17.8	(17.1)	162.0	(69.5)
December-05	10.7	(9.6)	19.1	(18.9)	113.4	(67.5)
January-06	11.9	(11.0)	21.4	(20.6)	26.0	(54.4)
February-06	11.3	(11.6)	21.4	(21.0)	8.0	(45.8)
March-06	10.8	(10.4)	20.5	(19.8)	23.2	(55.5)

4.6.2 *Plutella xylostella* (diamondback moth)

4.6.2.1 *P. xylostella* larvae and pupae numbers 04/05

P. xylostella larvae data from the 04/05 experiment indicate that there were significant differences between the different treatments, which first became evident at 26 DAT and continued until the final sample at 41 DAT (Figure 4.4). The LSD separations of the four treatments, designated by the different letters on the graph, illustrates that the treatments can be separated into two significantly different groups, with the two bare soil treatments having higher numbers of *P. xylostella* larvae compared to the cover crop treatments. This is further supported by the significance of the pairwise contrast of the cover crop and the bare soil treatments indicating that from 19 DAT, there were significantly fewer *P. xylostella* larvae in the cover crop treatments (Table 4.2). The results also indicate that apart from 19 DAT, there were no significant differences between strip cropping treatments and monoculture plots.

Figure 4.4. The mean number of *P.* xylostella larvae per plant sampled in 04/05 ± SE. "ns" not significant; * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

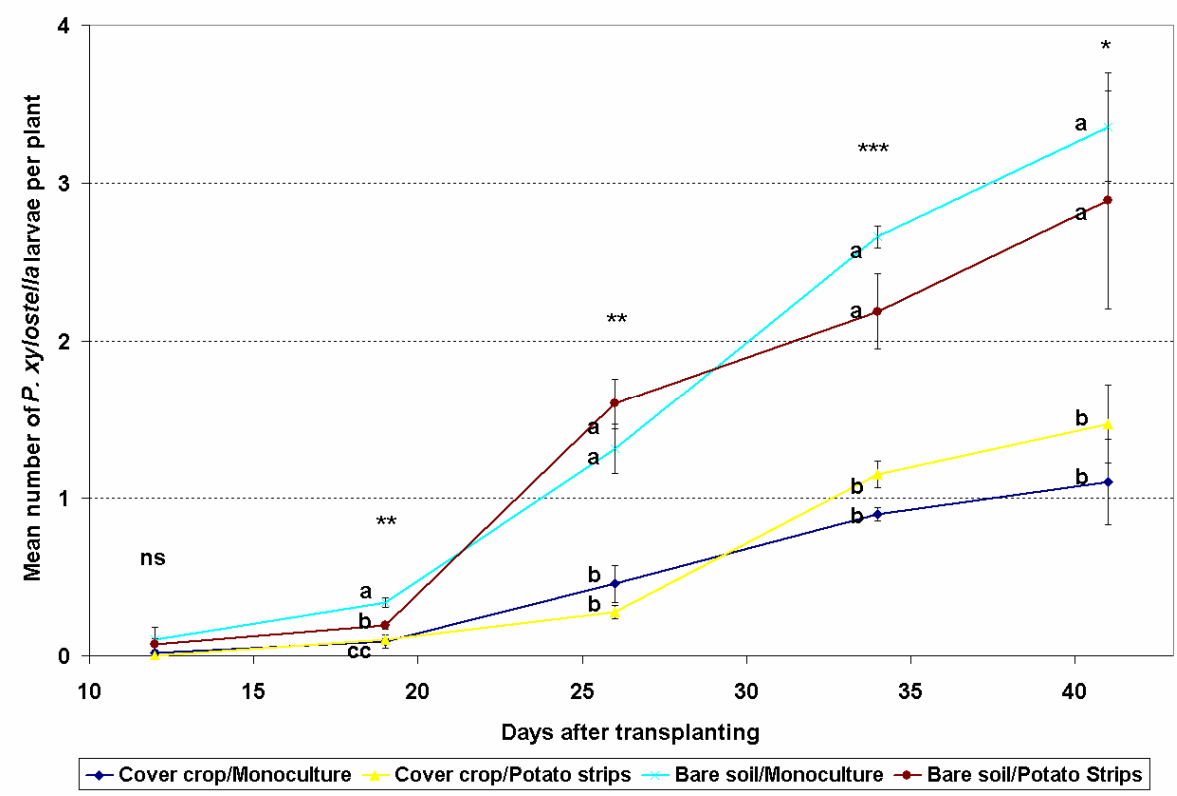


Table 4.2. The effect of treatment (four cropping systems) and planned comparisons of the abundance of *P. xylostella* larvae in 04/05. Significant results are shown in bold type.

12 days after transplanting	***df***	***F***	***P***
Treatment	3	1.07	0.3694
Contrasts			
Cover crop v. Bare soil	1	2.96	0.1362
Strip v. Monoculture	1	0.24	0.6406
19 days after transplanting	***df***	***F***	***P***
Treatment	3	19.13	**0.0018**
Contrasts			
Cover crop v. Bare soil	1	42.40	**0.0006**
Strip v. Monoculture	1	6.35	**0.0453**
26 days after transplanting	***df***	***F***	***P***
Treatment	3	20.21	**0.0015**
Contrasts			
Cover crop v. Bare soil	1	57.82	**0.0003**
Strip v. Monoculture	1	0.15	0.7114
34 days after transplanting	***df***	***F***	***P***
Treatment	3	36.54	**0.0003**
Contrasts			
Cover crop v. Bare soil	1	102.19	**<0.0001**
Strip v. Monoculture	1	0.64	0.4530
41 days after transplanting	***df***	***F***	***P***
Treatment	3	9.62	**0.0104**
Contrasts			
Cover crop v. Bare soil	1	27.45	**0.0019**
Strip v. Monoculture	1	0.02	0.9034

The examination of *P. xylostella* larvae for parasites indicated that there were no significant treatment effects (Table 4.3 and Table 4.4). Further analysis of the data using pairwise contrasts did not reveal any significant tests.

Table 4.3. Mean number of parasitised *P. xylostella* per 20 larvae from 04/05.

Treatment	Number (n)	Number of larvae parasitised ± SE	Percentage Parasitised
Cover crop/Monoculture	3	6.333 ± 1.333	31.65
Cover crop/Potato strips	3	6.333 ± 1.453	31.65
Bare soil/Monoculture	3	4.667 ± 0.333	23.34
Bare soil/Potato strips	3	4.333 ± 0.882	21.67

Table 4.4. The effect of treatment (four cropping systems) and planned comparisons of the parasitism rates of *P. xylostella* fourth instar larvae collected in 04/05.

	df	*F*	*P*
Treatment	3	1.32	0.3515
Contrasts			
Cover crop v. Bare soil	1	0.03	0.8630
Strip v. Monoculture	1	3.90	0.0956

The number of *P. xylostella* pupae per plant in 04/05 followed the same trend as the 04/05 larvae data except that the significant differences began at 34 DAT and not 26 DAT (Figure 4.5 and Table 4.5). The pairwise contrasts of the 04/05 pupae results indicated that the cover crop treatments had significantly fewer pupae at 26, 34 and 41 DAT, while there were no significant differences between the strip cropping and the monoculture treatments at any date.

Figure 4.5. The mean number of *P. xylostella* pupae per plant sampled in 04/05 ± SE. "ns" not significant; ** $P \leq 0.01$. Points without a letter in common are significantly different (P=0.05).

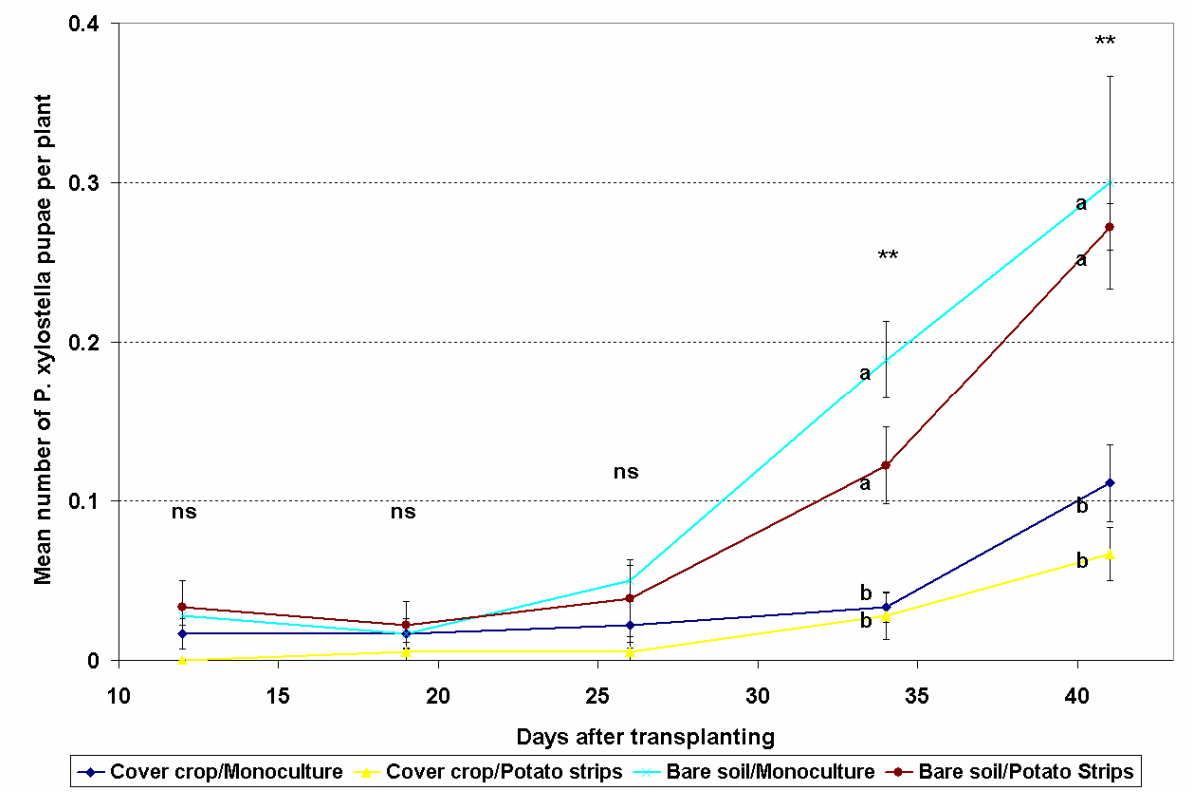


Table 4.5. The effect of treatment (four cropping systems) and planned comparisons of the abundance of *P. xylostella* pupae in 04/05. Significant results are shown in bold type.

12 days after transplanting	***df***	***F***	***P***
Treatment	3	1.75	0.2561
Contrasts			
Cover crop v. Bare soil	1	4.00	0.0924
Strip v. Monoculture	1	0.25	0.6349
19 days after transplanting	***df***	***F***	***P***
Treatment	3	0.39	0.7663
Contrasts			
Cover crop v. Bare soil	1	0.55	0.4859
Strip v. Monoculture	1	0.06	0.8128

26 days after transplanting	***df***	***F***	***P***
Treatment	3	2.58	0.1492
Contrasts			
Cover crop v. Bare soil	1	6.37	**0.0451**
Strip v. Monoculture	1	1.32	0.2950
34 days after transplanting	***df***	***F***	***P***
Treatment	3	12.51	**0.0054**
Contrasts			
Cover crop v. Bare soil	1	32.84	**0.0012**
Strip v. Monoculture	1	2.74	0.1489
41 days after transplanting	***df***	***F***	***P***
Treatment	3	10.90	**0.0077**
Contrasts			
Cover crop v. Bare soil	1	31.57	**0.0014**
Strip v. Monoculture	1	1.06	0.3432

4.6.2.2 *P. xylostella* adult numbers 05/06

The data from the vacuum sampling of adult moths at dusk showed a decline in the number of female moths over time (F=25.66, df=2, P<0.0001) with only one female captured in the final sample (Figure 4.6 and Table 4.6). The male moths also declined over time but not as significantly (F=3.61, df=2, P=0.0311). There was also a significant treatment difference in the number of males captured in the first vacuum sample taken (Figure 4.6 and Table 4.6). Pairwise contrasts of the female moth data did not indicate any significant differences in any sample, while the male moth data indicated that in the first sample there were significantly fewer male moths in the cover crop treatments compared to the bare soil treatments.

Figure 4.6. *P. xylostella* vacuum sampling results with female moths from the six treatments ± SE (left) and the male moths from the six treatments ± SE (right). Cc-M = Cover crop/Monoculture; Cc-Ry = Cover crop/Rye strips; Cc-Po = Cover crop/Potato strips; Bs-M = Bare soil/Monoculture; Bs-Ry = Bare soil /Rye strips; Bs-Po = Bare soil /Potato strips; Male moths captured 36 DAT (blue columns on the right) without a letter in common are significantly different (*P*=0.05).

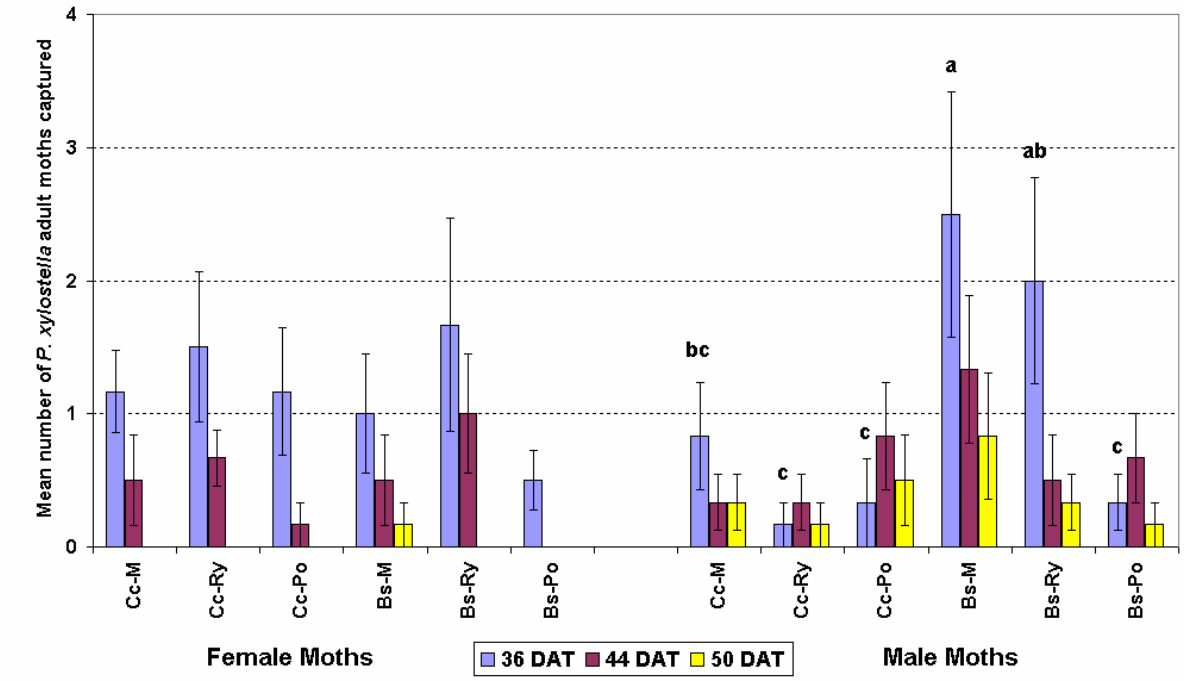


Table 4.6. The effect of treatment (six cropping systems) and planned comparisons of the abundance of *P. xylostella* adult moths in 05/06. Significant results are shown in bold type.

Female moths 36 days after transplanting	***df***	***F***	***P***
Treatment	5	0.80	0.5627
Contrasts			
Cover crop v. Bare soil	1	0.36	0.5577
Strip v. Monoculture	1	0.10	0.7551
Bare soil strip v. Bare soil monoculture	1	0.02	0.8830
Male moths 36 days after transplanting	***df***	***F***	***P***
Treatment	5	3.25	**0.0262**
Contrasts			
Cover crop v. Bare soil	1	6.83	**0.0167**
Strip v. Monoculture	1	4.09	0.0566
Bare soil strip v. Bare soil monoculture	1	3.96	0.0604

Female moths 44 days after transplanting	***df***	***F***	***P***
Treatment	5	2.01	0.1202
Contrasts			
Cover crop v. Bare soil	1	0.07	0.7890
Strip v. Monoculture	1	0.04	0.8499
Bare soil strip v. Bare soil monoculture	1	0.00	1.0000
Male moths 44 days after transplanting	***df***	***F***	***P***
Treatment	5	0.98	0.4534
Contrasts			
Cover crop v. Bare soil	1	1.13	0.3000
Strip v. Monoculture	1	0.57	0.4606
Bare soil strip v. Bare soil monoculture	1	2.55	0.1262
Male moths 50 days after transplanting	***df***	***F***	***P***
Treatment	5	0.74	0.6002
Contrasts			
Cover crop v. Bare soil	1	0.20	0.6616
Strip v. Monoculture	1	1.45	0.2434
Bare soil strip v. Bare soil monoculture	1	2.46	0.1322

The analysis of the oviposition experiment did not result in any significant treatment differences between the number of eggs oviposited by *P. xylostella* on leaf samples from different treatments (Table 4.7).

Table 4.7. Average number of eggs oviposited by *P. xylostella* on leaf samples in the adult moth laboratory cage ± SE.

Treatment	**Mean ± SE**
Cover crop / Monoculture	11.333 ± 2.848
Cover crop / Rye strips	3.667 ± 0.898
Cover crop / Potato strips	10.778 ± 2.994
Bare Soil / Monoculture	4.667 ± 2.007
Bare Soil / Rye strips	8.556 ± 3.671
Bare Soil / Potato strips	3.778 ± 1.321

Further examination of the ANOVA model indicates that random variation could explain most of the treatment differences observed (Table 4.8). The pairwise contrasts of the oviposition experiment data did not result in any significant tests.

Table 4.8. ANOVA model and planned comparisons of the number of eggs oviposited by *P. xylostella* on leaf samples in the adult moth laboratory cage in 05/06.

Model effects	*df*	Sum of Squares	*F*	*P*
Treatment	5	560.76	1.97	0.1012
Replication	2	71.26	0.63	0.5387
Tray	2	103.37	0.91	0.4099
Error	44	2498.70		
Contrasts				
Cover crop v. Bare soil	1		2.04	0.1608
Strip v. Monoculture	1		0.36	0.5515
Bare soil strip v. Bare soil monoculture	1		0.24	0.6283

4.6.2.3 *P. xylostella* egg numbers 05/06

Despite there being no significant differences between the number of adult females caught in different treatments and no significant oviposition preference for leaf samples from the different treatments, there were significantly more *P. xylostella* eggs on plants from the bare soil treatments compared to plants from the cover crop treatments (Figure 4.7). This was evident from the first sampling date at 14 DAT until 36 DAT. The number of eggs was only approaching significance at the final sampling date 44 DAT (P=0.0527), which is consistent with the reduction in the number of female moths captured over time in the vacuum samples. Highly significant treatment differences were also evident in the pairwise contrasts of the *P. xylostella* egg data, indicating that the cover crop treatments had significantly fewer eggs than the bare soil treatments up until the final sample taken at 44 DAT (Table 4.9). The pairwise contrasts of the strip crops and the monocultures, and of the bare soil strip crops and the bare soil monoculture were not significant.

Figure 4.7. The mean number of *P. xylostella* eggs per plant sampled in 05/06 ± SE. "ns" not significant; * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

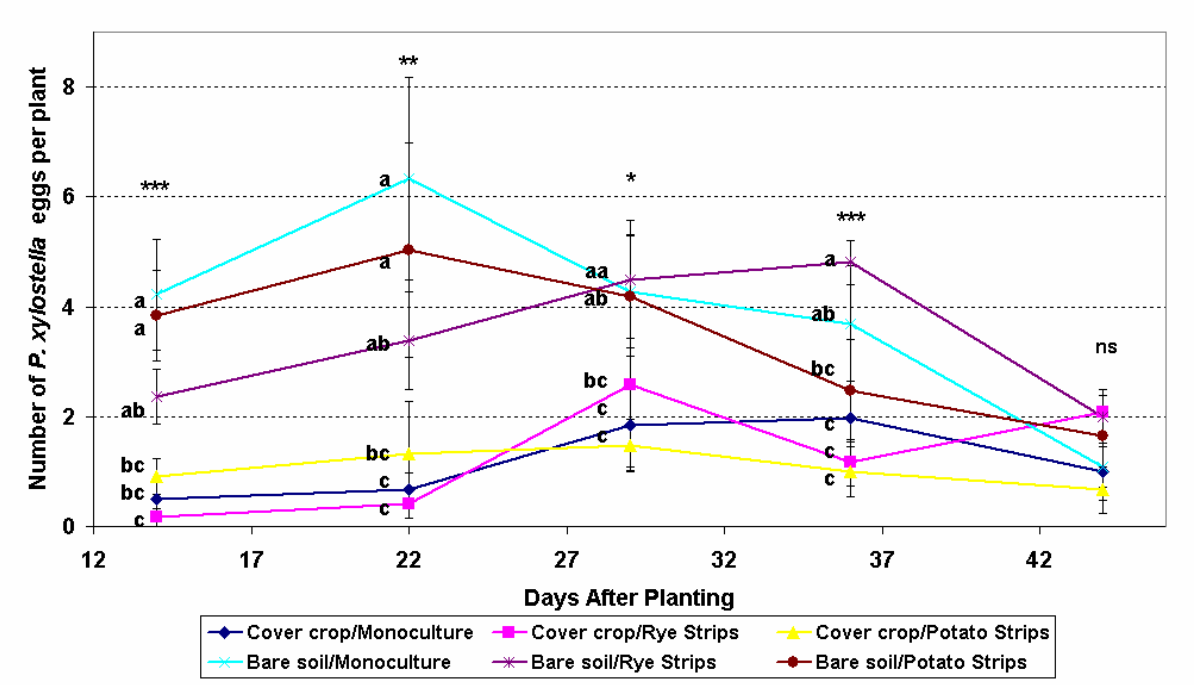


Table 4.9. The effect of treatment (six cropping systems) and planned comparisons of the abundance of *P. xylostella* eggs in 05/06. Significant results are shown in bold type.

14 days after transplanting	***df***	***F***	***P***
Treatment	5	6.93	**0.0007**
Contrasts			
Cover crop v. Bare soil	1	29.62	**<0.0001**
Strip v. Monoculture	1	0.89	0.3565
Bare soil strip v. Bare soil monoculture	1	1.92	0.1810
22 days after transplanting	***df***	***F***	***P***
Treatment	5	4.79	**0.0048**
Contrasts			
Cover crop v. Bare soil	1	22.71	**0.0001**
Strip v. Monoculture	1	0.28	0.6027
Bare soil strip v. Bare soil monoculture	1	0.52	0.4783

29 days after transplanting	***df***	***F***	***P***
Treatment	5	2.96	**0.0370**
Contrasts			
Cover crop v. Bare soil	1	14.69	**0.0010**
Strip v. Monoculture	1	0.01	0.9068
Bare soil strip v. Bare soil monoculture	1	0.00	0.9591
36 days after transplanting	***df***	***F***	***P***
Treatment	5	6.85	**0.0007**
Contrasts			
Cover crop v. Bare soil	1	24.14	**<0.0001**
Strip v. Monoculture	1	0.92	0.3483
Bare soil strip v. Bare soil monoculture	1	0.01	0.9371
44 days after transplanting	***df***	***F***	***P***
Treatment	5	2.67	0.0527
Contrasts			
Cover crop v. Bare soil	1	1.25	0.2769
Strip v. Monoculture	1	3.26	0.0859
Bare soil strip v. Bare soil monoculture	1	2.87	0.1060

Interpretation of the egg survival data from the exclusion cage experiment where gravid adult females were placed in cages surrounding plants in the field, was hindered by significant random variation in the number of eggs oviposited on different plants, which resulted in significant treatment differences (Table 4.10).

Table 4.10. Mean number of *P. xylostella* eggs oviposited on plants in exclusion cages in 05/06. Treatments without a letter in common are significantly different (*P*=0.05).

Treatment	**Mean ± SE**
Cover crop / Monoculture	9.667 ± 3.442 [ab]
Cover crop / Rye strips	5.000 ± 1.844 [b]
Cover crop / Potato strips	5.000 ± 1.238 [b]
Bare Soil / Monoculture	6.500 ± 0.719 [b]
Bare Soil / Rye strips	15.333 ± 2.044 [a]
Bare Soil / Potato strips	6.167 ± 1.956 [b]

When the treatments were separated using Fisher's LSD, the Bare soil/Rye strips treatment had significantly more eggs oviposited than all other treatments except the Cover crop/Monoculture. However, unlike the other *P. xylostella* data there were no apparent treatment groupings, which resulted in no significant contrasts (Table 4.11).

Table 4.11. The effect of treatment (six cropping systems) and planned comparisons of the abundance of *P. xylostella* eggs oviposited on plants in exclusion cages in 05/06. Significant results are shown in bold type.

	df	***F***	***P***
Treatment	5	3.68	**0.0159**
Contrasts			
Cover crop v. Bare soil	1	2.66	0.1186
Strip v. Monoculture	1	0.01	0.9093
Bare soil strip v. Bare soil monoculture	1	2.77	0.1118

Despite the differences in the number of eggs across treatments, the analysis of the caged egg survival data indicated that: eggs oviposited in the Cover crop/Monoculture treatment were approximately 2.7 times *more* likely to be attacked than hatched and 3.3 times *more* likely to be missing than hatched; eggs oviposited in the Cover crop/Rye strips treatment were approximately 3.3 times *less* likely to be attacked than hatched and 3.6 times *more* likely to be missing than hatched; and eggs oviposited in the Bare soil/Rye strips treatment were approximately 2.0 times *more* likely to be attacked than hatched and 2.2 times *less* likely to be missing than attacked (Table 4.12).

There were no eggs recovered from the second egg experiment where eggs from the laboratory population were placed on plants in the field. There was approximately 2mm of rainfall in the period between placing the eggs in the field and the assessment, which combined with slight changes in leaf angle from the horizontal may have been enough to wash the eggs from the plants.

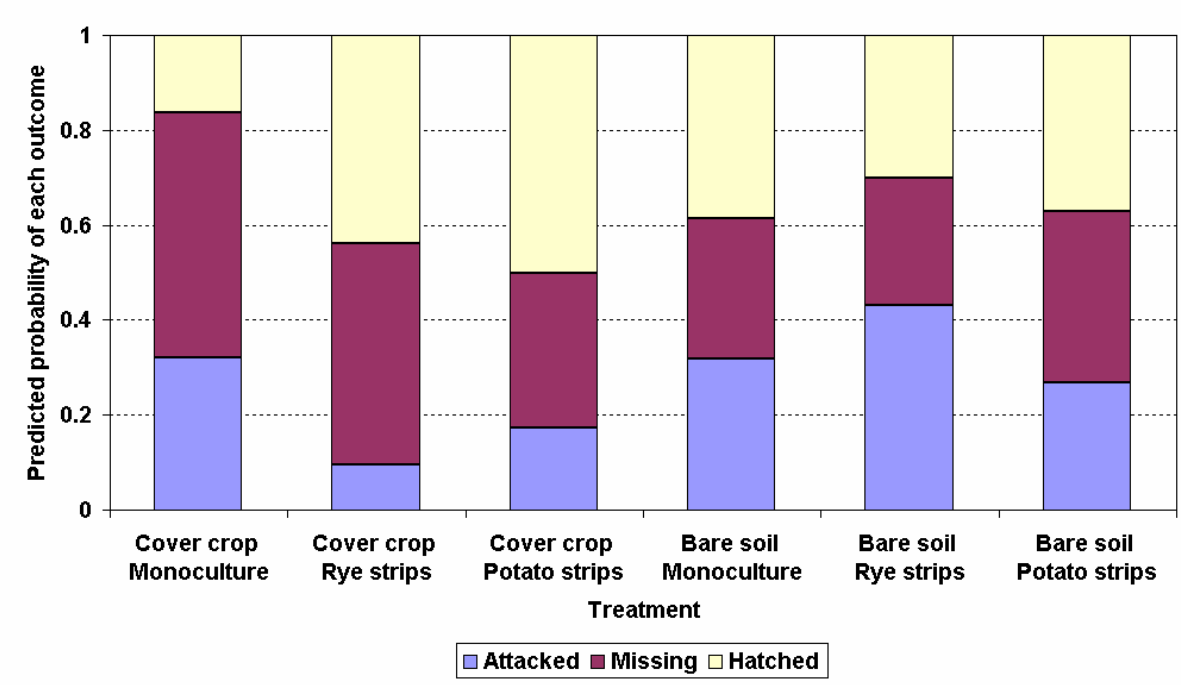
Table 4.12. Comparison of outcomes for *P. xylostella* eggs oviposited in the exclusion cage experiment.

Treatment	Comparison	Estimate	Likelihood	Standard Error	Wald Chi-Square	*P*
Cover Crop Monoculture	Attacked v. Hatched	1.004	2.729	0.413	5.914	**0.0150**
	Missing v. Hatched	1.185	3.271	0.405	8.564	**0.0034**
	Missing v. Attacked	0.181		0.386	0.220	0.6387
Cover Crop Rye Strips	Attacked v. Hatched	-1.188	3.280	0.591	4.044	**0.0443**
	Missing v. Hatched	0.087		0.467	0.035	0.8525
	Missing v. Attacked	1.275	3.579	0.6302	4.094	**0.0430**
Cover Crop Potato Strips	Attacked v. Hatched	-0.742		0.475	2.440	0.1183
	Missing v. Hatched	-0.397		0.457	0.756	0.3846
	Missing v. Attacked	0.345		0.5339	0.417	0.5183
Bare Soil Monoculture	Attacked v. Hatched	0.128		0.409	0.097	0.7550
	Missing v. Hatched	-0.244		0.401	0.373	0.5415
	Missing v. Attacked	-0.372		0.4266	0.762	0.3827
Bare Soil Rye Strips	Attacked v. Hatched	0.687	1.988	0.318	4.669	**0.0307**
	Missing v. Hatched	-0.083		0.323	0.065	0.7983
	Missing v. Attacked	-0.770	2.160	0.3301	5.438	**0.0197**
Bare Soil Potato Strips	Attacked v. Hatched	0.112		0.402	0.077	0.7808
	Missing v. Hatched	-0.547		0.467	1.373	0.2414
	Missing v. Attacked	-0.6509		0.4966	1.760	0.1846

When these results were expressed graphically it becomes more evident that there was a low probability of eggs hatching in the Cover crop/Monoculture treatment, a low probability of eggs being attacked in the Cover crop/Rye strips treatment and a high probability of eggs being attacked in the Bare soil/Rye strips treatment (Figure 4.8). Eggs in

the Cover crop/Potato strips treatment appear to have a high probability of hatching, however this was not significant due to high levels of within treatment variation and low numbers of oviposited eggs.

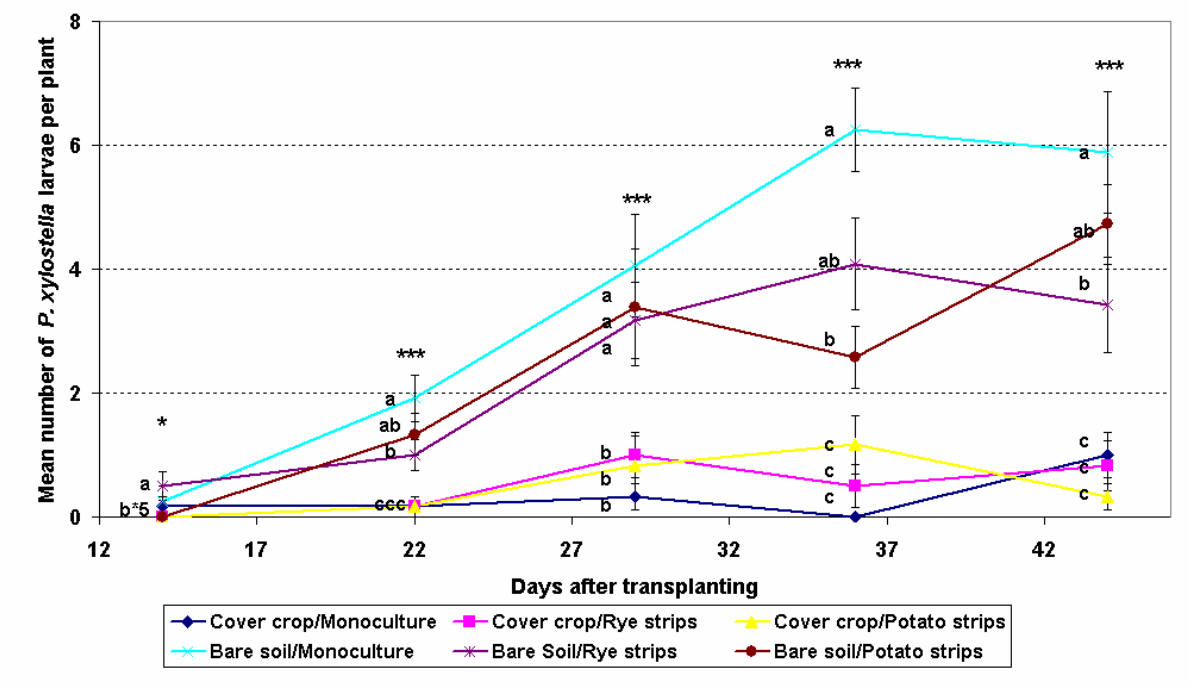
Figure 4.8. The probabilities of the three outcomes from the cage egg survival experiment where the eggs could have been predated (Attacked), hatched (Hatched) or were missing (Missing).



4.6.2.4 *P. xylostella* larvae and pupae numbers 05/06

The *P. xylostella* larvae results from the 05/06 experiment are similar to the larvae results from the 04/05 experiment in that the bare soil treatments had significantly higher numbers of larvae than the cover crop treatments from 22 DAT and there were no significant differences between any of the cover crop treatments at any of the sampling dates (Figure 4.9). However, there is some separation of the bare soil treatments at 14, 22 and 36 DAT, with the Bare soil/Rye strips treatment having higher larval numbers at 14 DAT, and the Bare soil/Monoculture treatment having higher larval numbers at 22 and 36 DAT. The pest numbers for the 05/06 experiment were approximately twice as large as the 04/05 experiment in the bare soil treatments, but equal or slightly lower in the cover crop treatments.

Figure 4.9. The mean number of *P. xylostella* larvae per plant sampled in 05/06 ± SE. "ns" not significant; * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).



The pairwise contrasts of the 05/06 larval data again indicate that the cover cropping treatments had significantly fewer *P. xylostella* larvae at all but the first sampling date (Table 4.13). The pairwise contrasts also indicate that the strip cropping treatments had significantly fewer larvae than the monoculture treatments at 22 DAT, largely due to the high number of larvae in the Bare soil/Monoculture plots. The bare soil strip cropping treatments (potato and rye) had significantly fewer larvae compared to the Bare soil/Monoculture treatment at 22, 36 and 44 DAT.

Table 4.13. The effect of treatment (six cropping systems) and planned comparisons of the abundance of *P. xylostella* larvae in 05/06. Significant results are shown in bold type.

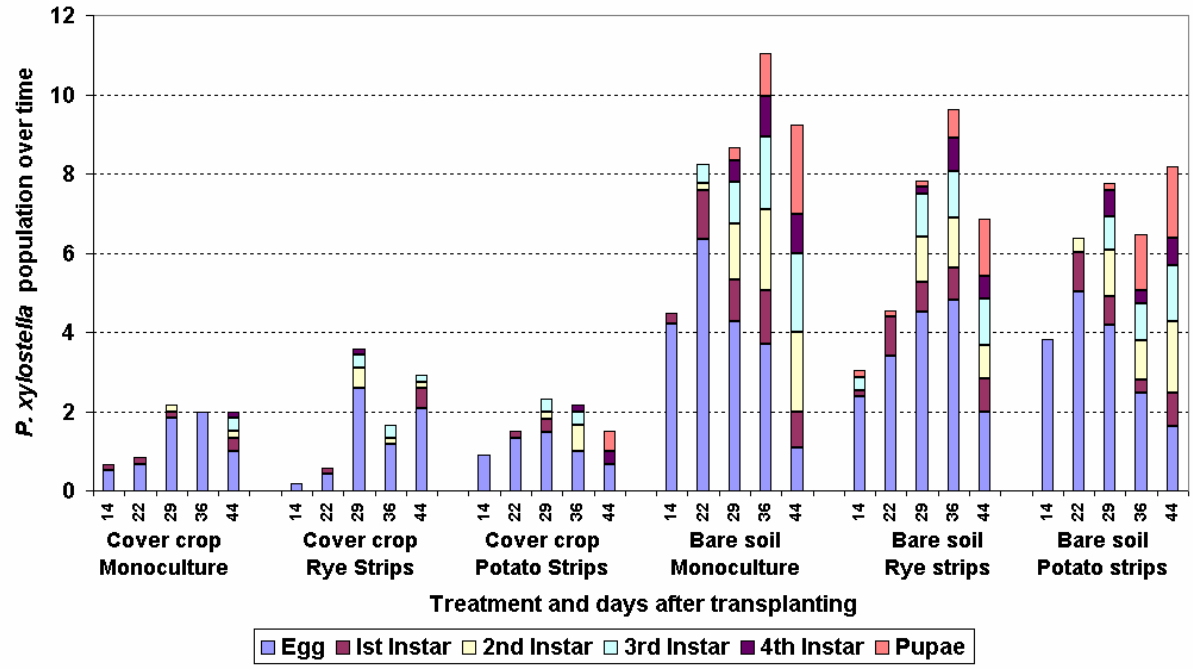
14 days after transplanting	***df***	***F***	***P***
Treatment	5	2.96	**0.0369**
Contrasts			
Cover crop v. Bare soil	1	3.95	0.0606
Strip v. Monoculture	1	0.00	1.0000
Bare soil strip v. Bare soil monoculture	1	0.52	0.4780
22 days after transplanting	***df***	***F***	***P***
Treatment	5	12.45	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	45.63	**<0.0001**
Strip v. Monoculture	1	7.89	**0.0108**
Bare soil strip v. Bare soil monoculture	1	15.79	**0.0007**
29 days after transplanting	***df***	***F***	***P***
Treatment	5	7.22	**0.0005**
Contrasts			
Cover crop v. Bare soil	1	34.20	**<0.0001**
Strip v. Monoculture	1	0.00	0.9747
Bare soil strip v. Bare soil monoculture	1	0.91	0.3525
36 days after transplanting	***df***	***F***	***P***
Treatment	5	15.42	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	57.73	**<0.0001**
Strip v. Monoculture	1	3.56	0.0738
Bare soil strip v. Bare soil monoculture	1	15.10	**0.0009**
44 days after transplanting	***df***	***F***	***P***
Treatment	5	10.22	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	44.86	**<0.0001**
Strip v. Monoculture	1	3.55	0.0741
Bare soil strip v. Bare soil monoculture	1	4.43	**0.0482**

Of the 103 pupae collected in the 05/06 experiment only three came from a cover crop treatment (Cover crop/Rye strips at 44 DAT), while the rest were evenly spread throughout

the remaining bare soil treatments with no significant differences between them (F=0.59, df=2, P=0.5587). All pupae collected were parasitised, with 101 *Diadegma* sp. (*D. semiclausum* (Hellén) and *D. rapi* (Cameron), Hymenoptera: Ichneumonidae) adults emerging and two *Diadromus collaris* (Gravenhorst, Hymenoptera: Ichneumonidae) adults.

The *P. xylostella* population summary from the 05/06 experiment, indicates that there were fewer eggs in the cover crop treatments when compared to the bare soil treatments, resulting in fewer larvae at all the recorded instars with virtually none pupating (Figure 4.10).

Figure 4.10. *P. xylostella* populations at each 05/06 sample as eggs, 1st, 2nd, 3rd and 4th instars or pupae.

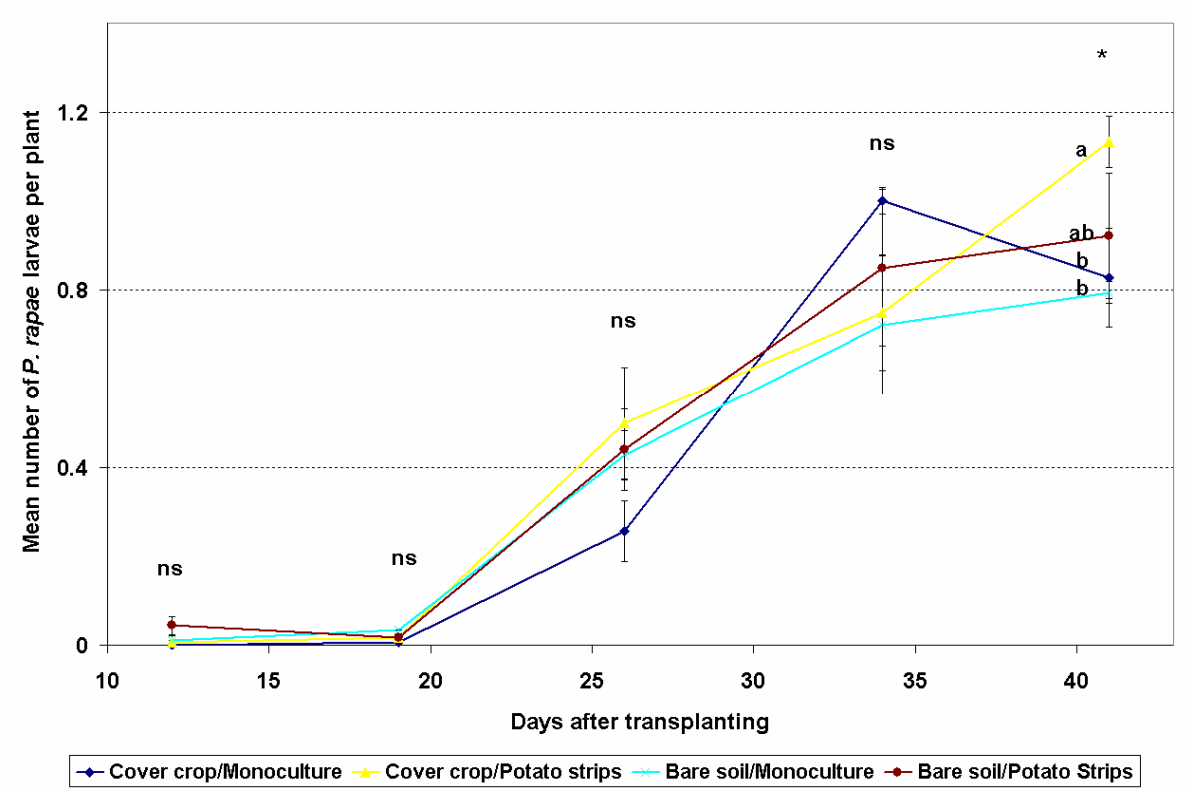


4.6.3 *Pieris rapae* (cabbage white butterfly)

4.6.3.1 *P. rapae* larvae numbers 04/05

The *P. rapae* larvae data from 04/05 differ from the 04/05 *P. xylostella* data in that there were no apparent differences between treatments as the larvae numbers generally increased over time in all treatments (Figure 4.11).

Figure 4.11. The mean number of *P. rapae* larvae per plant sampled in 04/05 ± SE. "ns" not significant; * $P \leq 0.05$. Points without a letter in common are significantly different (P=0.05).



However, there was a significant difference between the number of *P. rapae* larvae in the different treatments on the last sampling date at 41 DAT, with the Cover crop/Potato strips treatment being higher than both the monoculture treatments. This difference, when combined with the Bare soil/Potato strips data in the pairwise contrasts, led to a significant test at 41 DAT when the strip crops were compared to the monoculture plots. This meant that on the final sampling date, there were significantly more *P. rapae* larvae in the strip cropping plots compared to the monoculture plots (Table 4.14).

Table 4.14. The effect of treatment (four cropping systems) and planned comparisons of the abundance of *P. rapae* larvae in 04/05. Significant results are shown in bold type.

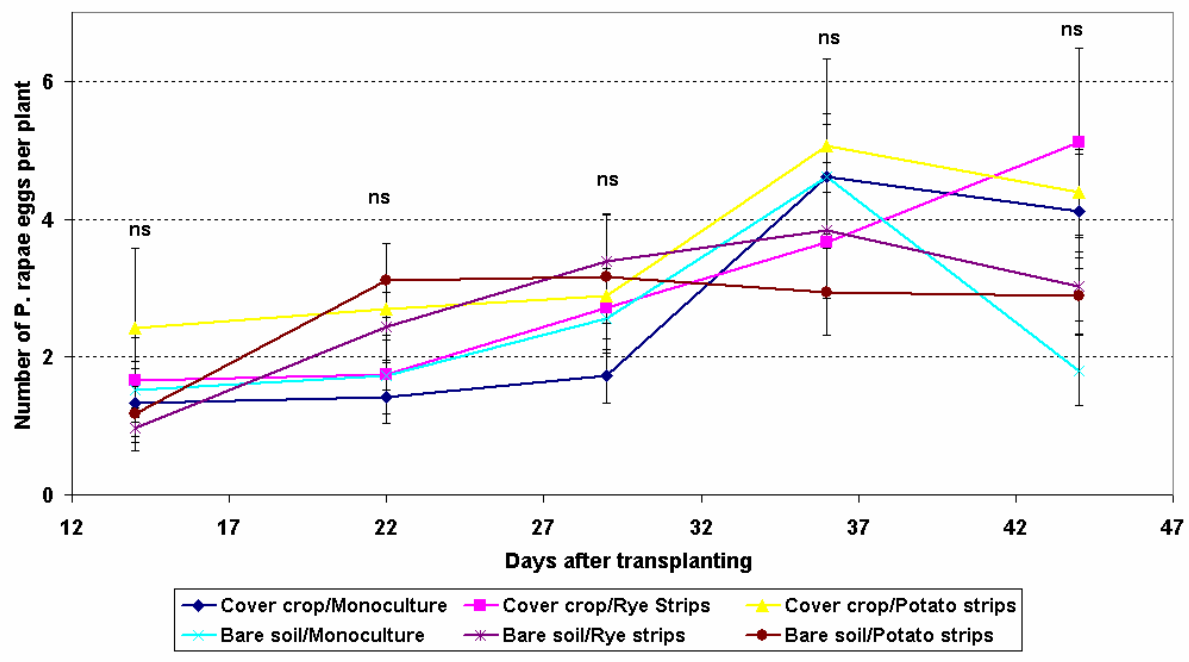
12 days after transplanting	***df***	***F***	***P***
Treatment	3	3.30	0.0995
Contrasts			
Cover crop v. Bare soil	1	5.17	0.0633
Strip v. Monoculture	1	3.13	0.1274

19 days after transplanting	***df***	***F***	***P***
Treatment	3	3.40	0.0946
Contrasts			
Cover crop v. Bare soil	1	4.99	0.0668
Strip v. Monoculture	1	0.20	0.6726
26 days after transplanting	***df***	***F***	***P***
Treatment	3	1.40	0.3307
Contrasts			
Cover crop v. Bare soil	1	0.39	0.5538
Strip v. Monoculture	1	2.08	0.1994
34 days after transplanting	***df***	***F***	***P***
Treatment	3	4.56	0.0543
Contrasts			
Cover crop v. Bare soil	1	2.29	0.1813
Strip v. Monoculture	1	1.08	0.3387
41 days after transplanting	***df***	***F***	***P***
Treatment	3	4.90	**0.0470**
Contrasts			
Cover crop v. Bare soil	1	3.15	0.1263
Strip v. Monoculture	1	9.90	**0.0199**

4.6.3.2 *P. rapae* egg numbers 05/06

The *P. rapae* egg data collected from the 05/06 experiment indicates that, unlike the *P. xylostella* egg data from 05/06, there were no significant differences between the number of eggs oviposited by *P. rapae* adults in the different treatments (Figure 4.12). While the numbers of eggs oviposited in most cases increased over time, there was significant random variation between treatments and sampling dates.

Figure 4.12. The mean number of *P. rapae* eggs per plant sampled in 05/06 ± SE. "ns" indicates that there were no significant differences for that sampling date.



Although there were no significant differences evident in the number of *P. rapae* eggs oviposited in each treatment, pairwise contrasts of the data resulted in two significant tests. The Bare soil/Monoculture treatment had a substantial reduction in the number of eggs between the samples collected 36DAT and 44DAT, which explains why the cover crop treatments had significantly higher egg numbers than the bare soil treatments at 44 DAT. Conversely, the low number of eggs in the Cover crop/Monoculture treatment at 22 DAT, resulted in the monoculture treatments having significantly fewer eggs than the strip crop treatments at 22 DAT.

Table 4.15. The effect of treatment (six cropping systems) and planned comparisons of the abundance of *P. rapae* eggs in 05/06. Significant results are shown in bold type.

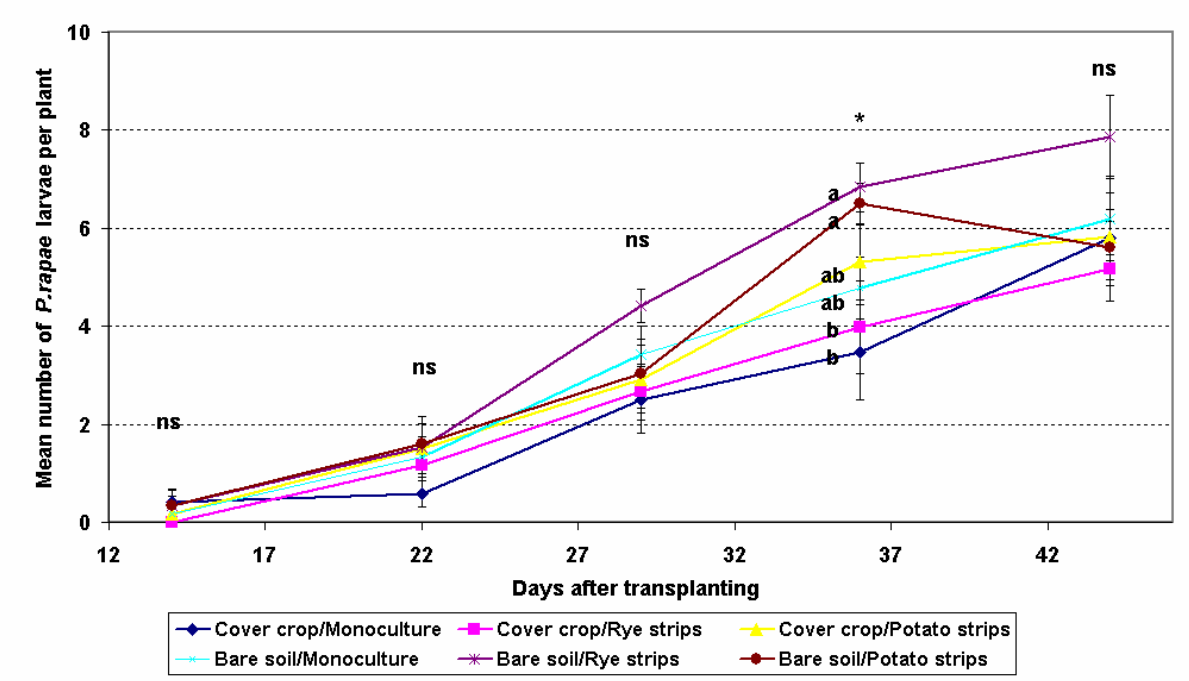
14 days after transplanting	***df***	***F***	***P***
Treatment	5	0.50	0.7703
Contrasts			
Cover crop v. Bare soil	1	0.72	0.4072
Strip v. Monoculture	1	0.00	0.9540
Bare soil strip v. Bare soil monoculture	1	0.74	0.4001

22 days after transplanting	***df***	***F***	***P***
Treatment	5	2.30	0.0830
Contrasts			
Cover crop v. Bare soil	1	1.77	0.1984
Strip v. Monoculture	1	6.11	**0.0226**
Bare soil strip v. Bare soil monoculture	1	3.93	0.0613
29 days after transplanting	***df***	***F***	***P***
Treatment	5	0.96	0.4639
Contrasts			
Cover crop v. Bare soil	1	1.49	0.2357
Strip v. Monoculture	1	3.08	0.0944
Bare soil strip v. Bare soil monoculture	1	0.99	0.3324
36 days after transplanting	***df***	***F***	***P***
Treatment	5	0.76	0.5922
Contrasts			
Cover crop v. Bare soil	1	0.79	0.3858
Strip v. Monoculture	1	0.90	0.3538
Bare soil strip v. Bare soil monoculture	1	1.24	0.2782
44 days after transplanting	***df***	***F***	***P***
Treatment	5	2.10	0.1078
Contrasts			
Cover crop v. Bare soil	1	8.42	**0.0088**
Strip v. Monoculture	1	1.56	0.2263
Bare soil strip v. Bare soil monoculture	1	1.29	0.2694

4.6.3.3 *P. rapae* larvae numbers 05/06

The *P. rapae* larvae results from the 05/06 experiment show a similar trend to the 04/05 *P. rapae* results, with a steady increase in larvae numbers over time (Figure 4.13). Unlike the *P. xylostella* larvae data from both 04/05 and 05/06, there are no obvious treatment differences or treatment groupings. It should also be noted that the numbers of *P. rapae* larvae at each sampling date were approximately five times higher in 05/06 than the previous season.

Figure 4.13. The mean number of *P. rapae* larvae per plant sampled in 05/06 ± SE. "ns" not significant; * $P \leq 0.05$. Points without a letter in common are significantly different (P=0.05).



There was a significant treatment difference at 36 DAT. This difference was also reflected in the two significant pairwise contrasts at the same sampling date, with the cover crop treatments having fewer *P. rapae* larvae than the bare soil treatments and the monoculture treatments having fewer than the strip cropping treatments (Table 4.16).

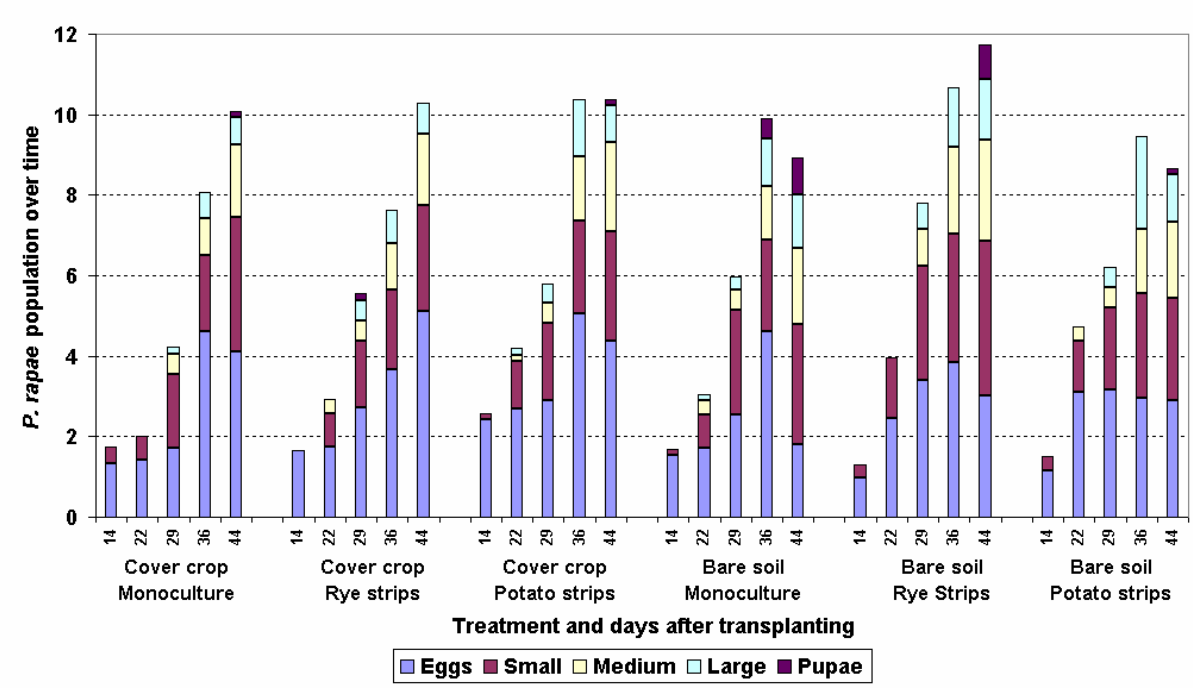
Table 4.16. The effect of treatment (six cropping systems) and planned comparisons of the abundance of *P. rapae* larvae in 05/06. Significant results are shown in bold type.

14 days after transplanting	***df***	***F***	***P***
Treatment	5	0.39	0.8478
Contrasts			
Cover crop v. Bare soil	1	0.18	0.6801
Strip v. Monoculture	1	0.16	0.6974
Bare soil strip v. Bare soil monoculture	1	0.31	0.5831

22 days after transplanting	***df***	***F***	***P***
Treatment	5	0.97	0.4586
Contrasts			
Cover crop v. Bare soil	1	1.68	0.2097
Strip v. Monoculture	1	2.19	0.1547
Bare soil strip v. Bare soil monoculture	1	0.25	0.6220
29 days after transplanting	***df***	***F***	***P***
Treatment	5	1.22	0.3382
Contrasts			
Cover crop v. Bare soil	1	3.25	0.0863
Strip v. Monoculture	1	0.30	0.5894
Bare soil strip v. Bare soil monoculture	1	0.16	0.6956
36 days after transplanting	***df***	***F***	***P***
Treatment	5	3.24	0.0266
Contrasts			
Cover crop v. Bare soil	1	8.59	**0.0083**
Strip v. Monoculture	1	5.58	**0.0284**
Bare soil strip v. Bare soil monoculture	1	4.27	0.0521
44 days after transplanting	***df***	***F***	***P***
Treatment	5	1.92	0.1359
Contrasts			
Cover crop v. Bare soil	1	2.99	0.0990
Strip v. Monoculture	1	0.04	0.8420
Bare soil strip v. Bare soil monoculture	1	0.43	0.5199

All the *P. rapae* data collected from the 05/06 experiment is summarised in Figure 4.14. This graph indicates that the *P. rapae* population is much more evenly distributed amongst treatments than the *P. xylostella* population summary illustrated by Figure 4.10.

Figure 4.14. *P. rapae* populations at each 05/06 sampling date summarised as: eggs; 1st and 2nd instar (small) ; 3rd and 4th instars (medium); 5th instar (large); and pupae.



P. rapae pupae were first recorded on the 4th census date in both the 04/05 and 05/06 seasons and due to the low numbers recorded (29 in 2004/2005 and 21 in 2005/2006) pupal data from *P. rapae* could not be statistically analysed and are not presented. The low number of *P. rapae* pupae present in both seasons could be due to movement of *P. rapae* larvae into neighbouring plant material or crops, therefore avoiding detection, as *P. rapae* will move from the natal plant to pupate (Waterhouse and Sands 2001). This is demonstrated in a picture taken in the strip cropping trial conducted in 2003/2004, where a *P. rapae* larva has moved from a broccoli plant and pupated on a neighbouring onion plant (Picture 4.9).

Picture 4.9. *P. rapae* pupating on an onion plant.

4.6.4 *Brevicoryne brassicae* (cabbage aphid)

4.6.4.1 *B. brassicae* colonies 04/05

There were significant treatment differences in the colonisation rate of *B. brassicae* evident from the first census at 12 DAT until 34 DAT (Figure 4.15). For the first two samples, the Bare soil/Potato strips treatment had a significantly higher number of *B. brassicae* colonies than all other treatments, while the Bare soil/Monoculture treatment had significantly higher numbers than the two cover cropping treatments. For the third and fourth samples there were no significant differences between the bare soil treatments, but there were significant differences between the bare soil and the cover crop treatments. Unlike the *P. xylostella* larvae data from 04/05, the differences between the treatments diminished as the broccoli crop grew until there were no significant differences between any treatments at the final sample (41 DAT).

The same trends are also evident in the pairwise contrasts of the *B. brassicae* data (Table 4.17). For the samples collected at 12 and 19 DAT, there were significantly greater *B. brassicae* numbers in the bare soil treatments compared to the cover crop treatments and significantly greater numbers in the Bare soil/Potato strips treatment compared to the Bare soil/Monoculture treatment. Similar results were obtained from the sample 26 DAT except that the contrast between the Bare soil/ Potato strips and the Bare soil/Monoculture treatments was very close to significance (P=0.0501). For the contrast of all the remaining

samples there were significant differences between the cover crop treatments and the bare soil treatments, although the significance level reduced with time.

Figure 4.15. The percentage of sampled plants in 04/05 with *B. brassicae* colonies present. "ns" not significant; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

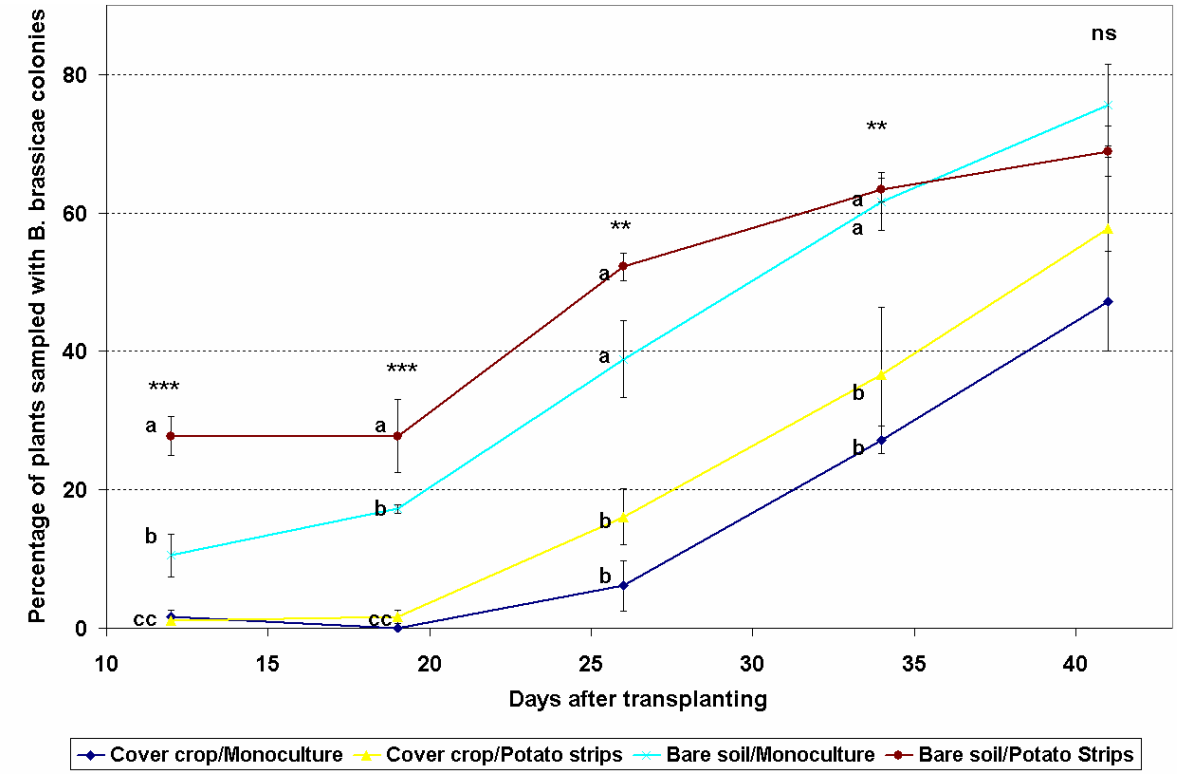


Table 4.17. The effect of treatment (four cropping systems) and planned comparisons of the proportion of sampled plants with *B. brassicae* colonies in 04/05. Significant results are shown in bold type.

12 days after transplanting	***df***	***F***	***P***
Treatment	3	29.23	**0.0006**
Contrasts			
Cover crop v. Bare soil	1	71.67	**0.0001**
Strip v. Monoculture	1	6.75	**0.0407**
19 days after transplanting	***df***	***F***	***P***
Treatment	3	50.70	**0.0001**
Contrasts			
Cover crop v. Bare soil	1	142.34	**<0.0001**
Strip v. Monoculture	1	9.70	**0.0207**

26 days after transplanting	***df***	***F***	***P***
Treatment	3	16.53	**0.0026**
Contrasts			
Cover crop v. Bare soil	1	43.51	**0.0006**
Strip v. Monoculture	1	5.98	0.0501
34 days after transplanting	***df***	***F***	***P***
Treatment	3	13.08	**0.0048**
Contrasts			
Cover crop v. Bare soil	1	37.51	**0.0009**
Strip v. Monoculture	1	1.15	0.3240
41 days after transplanting	***df***	***F***	***P***
Treatment	3	2.93	0.1216
Contrasts			
Cover crop v. Bare soil	1	7.26	**0.0358**
Strip v. Monoculture	1	0.04	0.8558

4.6.4.2 *B. brassicae* parasitism 04/05

The level of *B. brassicae* parasitism by *Diaeretiella rapae* was recorded at each census as the presence or absence of parasitised "mummies" (Figure 4.16 and Table 4.18). There were no mummies present at the first sample taken 12 DAT, but from the second sample at 19 DAT onwards there was evidence of parasitism and significant differences across the treatments. The rate of parasitism in the strip cropping treatments was significantly higher than the three other treatments at 19 and 26 DAT, with numbers peaking at 26 DAT and then steadily declining for the remaining samples. The parasitism rates for the other treatments appeared to increase up until the final sample 41 DAT. The overall higher rate of parasitism in the Bare soil/Monoculture and Bare soil/Potato strips treatments probably reflects the initially higher numbers of *B. brassicae* colonies illustrated by Figure 4.15. That is, greater aphid numbers led to greater parasitism.

Figure 4.16. The percentage of plants sampled in 04/05 with parasitised *B. brassicae*. ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

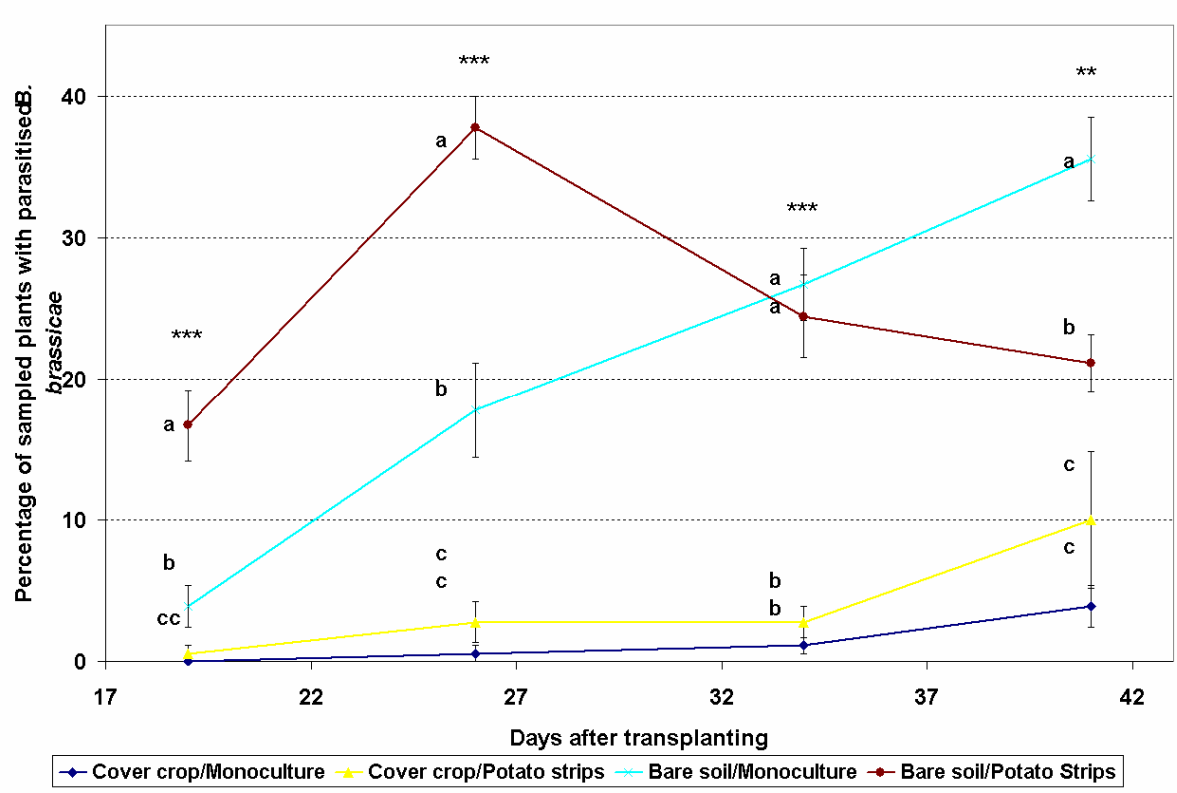


Table 4.18. The effect of treatment (four cropping systems) and planned comparisons of the proportion of sampled plants with parasitised *B. brassicae* in 04/05. Significant results are shown in bold type.

19 days after transplanting	***df***	***F***	***P***
Treatment	3	24.22	**0.0009**
Contrasts			
Cover crop v. Bare soil	1	54.53	**0.0003**
Strip v. Monoculture	1	12.40	**0.0125**
26 days after transplanting	***df***	***F***	***P***
Treatment	3	26.32	**0.0007**
Contrasts			
Cover crop v. Bare soil	1	68.82	**0.0002**
Strip v. Monoculture	1	8.60	**0.0262**

34 days after transplanting	***df***	***F***	***P***
Treatment	3	34.73	**0.0003**
Contrasts			
Cover crop v. Bare soil	1	102.23	**<0.0001**
Strip v. Monoculture	1	0.38	0.5610
41 days after transplanting	***df***	***F***	***P***
Treatment	3	14.63	**0.0036**
Contrasts			
Cover crop v. Bare soil	1	36.84	**0.0009**
Strip v. Monoculture	1	0.29	0.6114

4.6.4.3 *B. brassicae* colonies 05/06

There were significant treatment differences in the number of alate *B. brassicae* recorded in all four samples in 05/06 (Figure 4.17). Like the *P. xylostella* data from 05/06, the number of alate *B. brassicae* were significantly higher in the bare soil treatments compared to the cover crop treatments, although there was some treatment overlap at 29 and 36 DAT indicated by the LSD's. When these results were analysed using pairwise contrasts there were very significant differences with greater numbers of alate *B. brassicae* in bare soil treatments compared to cover crop treatments (Table 4.19). This indicates that *B. brassicae* was less effective at colonising broccoli planted in a cover crop compared to bare soil.

Figure 4.17. The mean number of alate *B. brassicae* per plant sampled in 05/06. ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

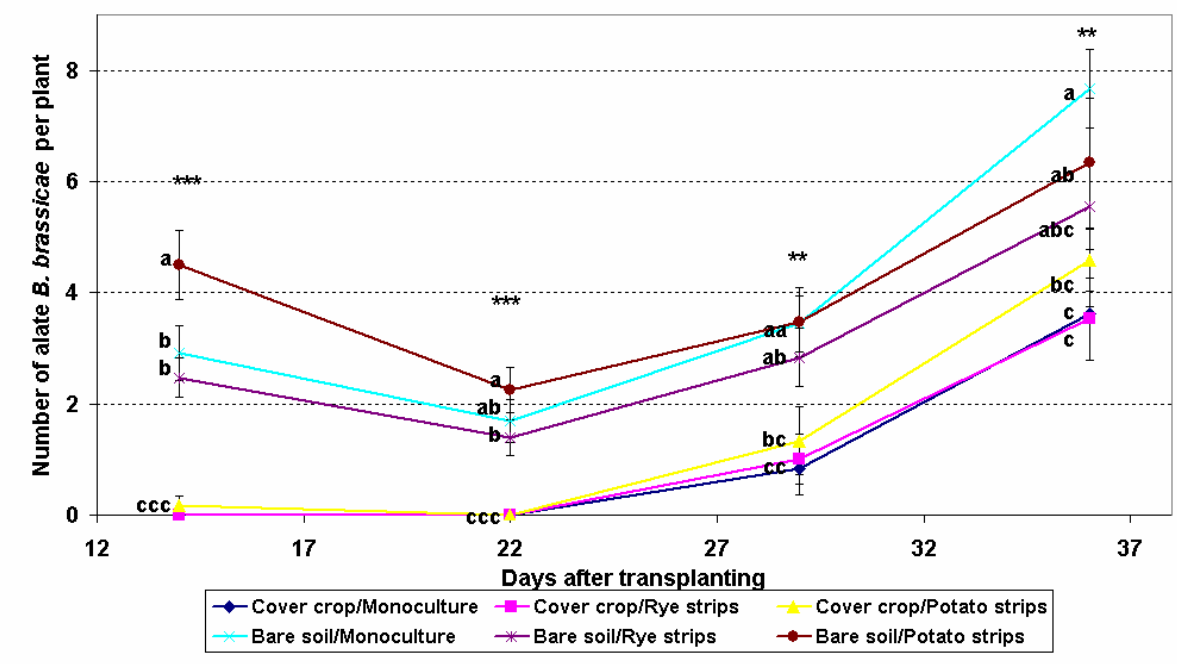


Table 4.19. The effect of treatment (six cropping systems) and planned comparisons of the abundance of alate *B. brassicae* in 05/06. Significant results are shown in bold type.

14 days after transplanting	***df***	***F***	***P***
Treatment	5	53.17	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	254.56	**<0.0001**
Strip v. Monoculture	1	0.93	0.3473
Bare soil strip v. Bare soil monoculture	1	0.83	0.3730
22 days after transplanting	***df***	***F***	***P***
Treatment	5	15.12	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	69.98	**<0.0001**
Strip v. Monoculture	1	0.08	0.7844
Bare soil strip v. Bare soil monoculture	1	0.15	0.6991

29 days after transplanting	***df***	***F***	***P***
Treatment	5	4.72	**0.0052**
Contrasts			
Cover crop v. Bare soil	1	22.38	**0.0001**
Strip v. Monoculture	1	0.00	0.9666
Bare soil strip v. Bare soil monoculture	1	0.18	0.6796
36 days after transplanting	***df***	***F***	***P***
Treatment	5	4.49	**0.0066**
Contrasts			
Cover crop v. Bare soil	1	17.40	**0.0005**
Strip v. Monoculture	1	0.93	0.3474
Bare soil strip v. Bare soil monoculture	1	3.36	0.0816

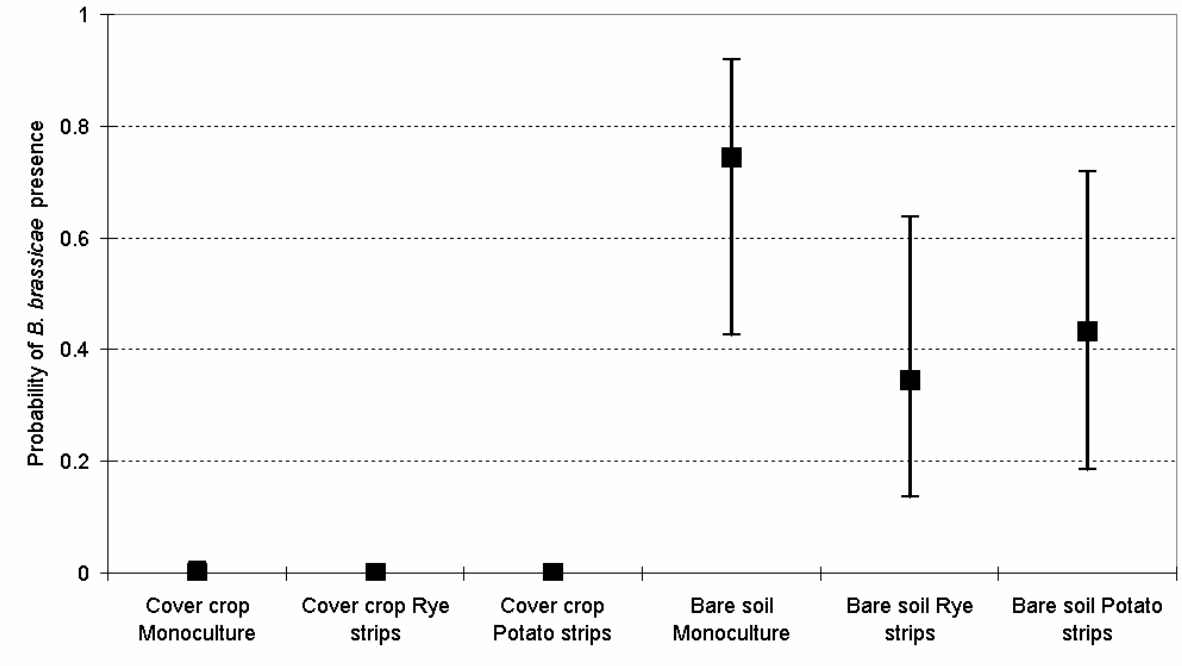
When the logistic regression results for the probability of plants being infested with *B. brassicae* colonies were presented in a matrix format, the bare soil treatments had a much greater chance of harbouring *B. brassicae* colonies than the cover crop treatments (log odds of 7.7 to 10.6 times greater) (Table 4.20). This overall result was compatible with the differences in colonisation illustrated by the alate *B. brassicae* data. Table 4.20 also indicates that there were no significant differences in the chance of infestation within the cover crop treatments and that the Bare soil/Monoculture treatment had a slightly greater chance of infestation than the Bare soil/Potato strip and the Bare soil/Rye strips treatments (with log odds of 1.3 and 1.7 time greater respectively).

Table 4.20. *B. brassicae* colonies in 05/06 logistic regression estimates with *P* values in brackets. Significant tests are shown in bold type.

	Cover crop Monoculture	Cover crop Rye Strips	Cover crop Potato strips	Bare soil Monoculture	Bare soil Rye strips
Cover crop Rye strips	0.56 (*P*=0.3298)				
Cover crop Potato strips	-0.62 (*P*=0.3379)	-1.17 (*P*=0.0586)			
Bare soil Monoculture	10.04 **(*P*<0.0001)**	10.66 **(*P*<0.0001)**	9.48 **(*P*<0.0001)**		
Bare Soil Rye strips	8.33 **(*P*<0.0001)**	8.95 **(*P*<0.0001)**	7.77 **(*P*<0.0001)**	-1.71 **(*P*=0.0054)**	
Bare soil Potato strips	8.70 **(*P*<0.0001)**	9.32 **(*P*<0.0001)**	8.14 **(*P*<0.0001)**	-1.34 **(*P*=0.0299)**	0.3703 (*P*=0.4549)

When the probability of aphids being present in each individual treatment was expressed graphically with the inclusion of 95% confidence intervals, it was evident that there was a very low probability of *B. brassicae* infestation in the cover crop treatments (Figure 4.18). Furthermore, the Bare soil/Potato strips and the Bare soil/Rye strips treatments had a lower probability of infestation than the Bare soil/Monoculture. This provides evidence that the cover crop and possibly the level of field fragmentation had a significant negative effect on the number of *B. brassicae* colonies in cropping systems.

Figure 4.18. The probability of *B. brassicae* presence on broccoli plants with 95% confidence intervals.



4.6.4.4 *B. brassicae* parasitism 05/06

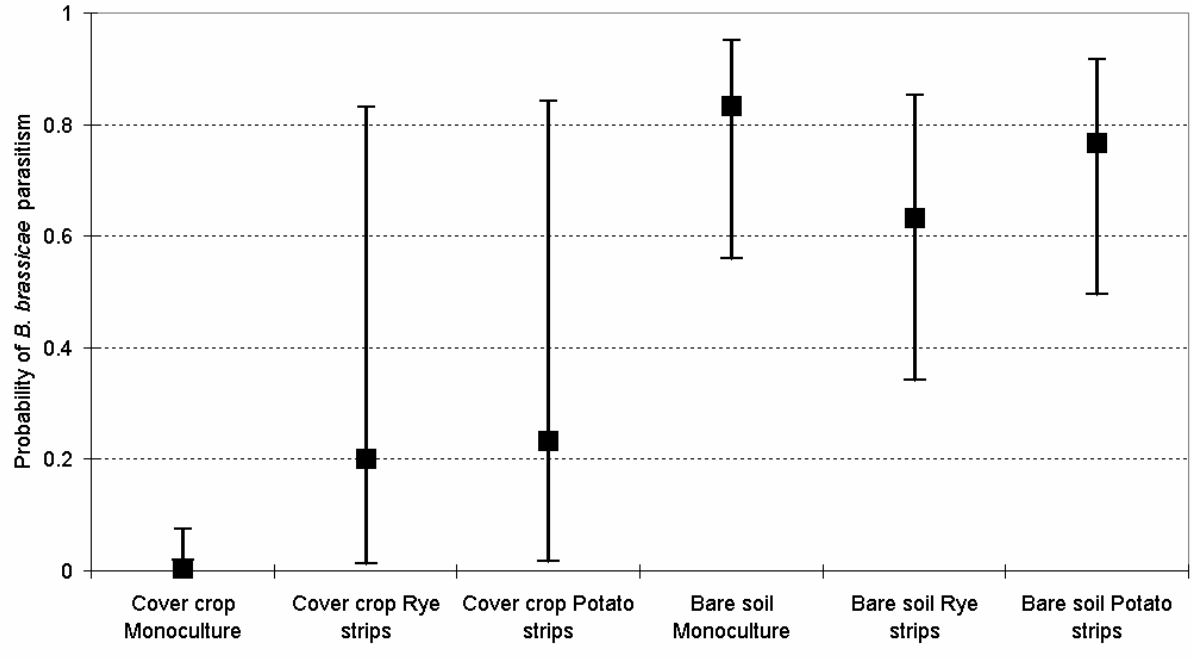
Analysis of the *B. brassicae* parasitism data detected quasi-complete separation on some blocking variables. This occurs when the outcome variable is almost completely explained by the explanatory variables. Since this can result in unstable estimates these variables were removed and the analysis repeated. This means that the latin square design (Block and Row) and the sampling date (Replication) were not taken into account in the model. Using this process the variation that was explained by the blocking variables was now explained by the treatments alone, which resulted in large variations. However, the same trends identified in the *B. brassicae* colonies data from 05/06 were present in the logistic regression matrix of *B. brassicae* parasitism, except that the regression estimates were lower (Table 4.21).

Table 4.21. *B. brassicae* parasitism in 05/06 logistic regression estimates with *P* values in brackets. Significant tests are in bold type.

	Cover crop Monoculture	**Cover crop Rye Strips**	**Cover crop Potato strips**	**Bare soil Monoculture**	**Bare soil Rye strips**
Cover crop Rye strips	0.81 (*P*=0.0648)				
Cover crop Potato strips	1.01 **(*P*=0.0193)**	0.20 (*P*=0.5876)			
Bare soil Monoculture	3.81 **(*P*<0.0001)**	3.00 **(*P*<0.0001)**	2.80 **(*P*<0.0001)**		
Bare Soil Rye strips	2.74 **(*P*<0.0001)**	1.93 **(*P*<0.0001)**	1.73 **(*P*<0.0001)**	-1.06 **(*P*=0.0030)**	
Bare soil Potato strips	3.39 **(*P*<0.0001)**	2.58 **(*P*<0.0001)**	2.38 **(*P*<0.0001)**	-0.42 **(*P*<0.0001)**	0.64 (*P*=0.0525)

When the probability of aphids being parasitised in each individual treatment was expressed graphically with the inclusion of 95% confidence intervals, large variations caused by the removal of blocking variables were evident (Figure 4.19). However, there appears to be a greater probability of finding evidence of parasitism (mummies) in the cover crop treatments than finding live colonies in the cover crops, especially in the Cover crop/Potato strips and the Cover crop/Rye strips treatments. The results from the bare soil treatments are an approximation of the *B. brassicae* colonies data except that the probability of parasitism was generally higher. This indicates that there was a greater probability of finding parasitised aphids in the bare soil treatments than live colonies.

Figure 4.19. Probability of *B. brassicae* parasitism with 95% confidence intervals.



4.6.5 Semi-commercial Trial

The extension of the cover crop treatment into a semi-commercial area supported the data from the two experiments at Forthside in 04/05 and 05/06 (Figure 4.20 and Table 4.22). There were significantly higher numbers of *P. xylostella* larvae and *B. brassicae* colonies in the bare soil treatment when compared to the cover crop treatment, and no significant treatment differences between *P. rapae* eggs and larvae numbers. The *P. xylostella* egg data was very close to significance at P=0.051. When the low statistical power of the analysis (due to only two error degrees of freedom) and a significant Block effect of this particular analysis (F=59.00, df=3, P=0.0167) were taken into account, this result is also consistent with the *P. xylostella* egg results from the 05/06 experiment at Forthside.

Figure 4.20. Mean number of various insects and eggs from the semi-commercial trial at Gawler taken 23 DAT in 05 ± SE. "ns" not significant; * $P \leq 0.05$.

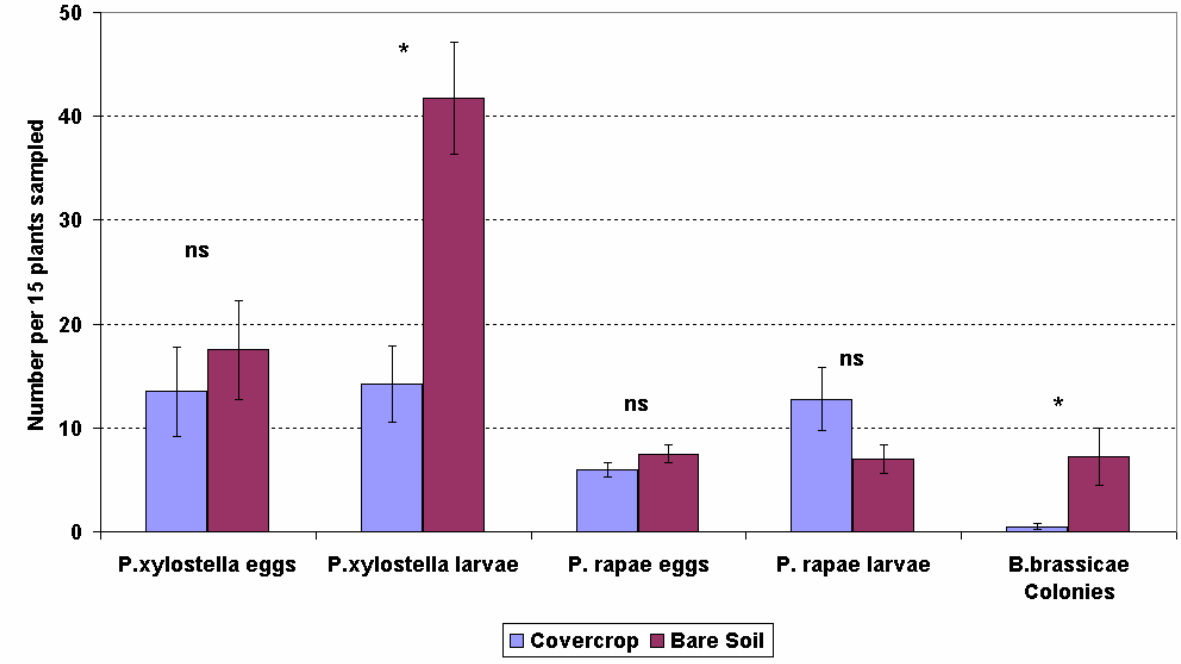


Table 4.22. The effect of treatment (Cover crop and Bare soil) on the abundance of insects in the semi-commercial trial at Gawler in 05/06. Significant results are shown in bold type.

Insect and stage	*df*	*F*	*P*
P. xylostella larvae	3	36.96	**0.0260**
P. xylostella eggs	3	18.06	0.0512
P. rapae larvae	3	2.56	0.2506
P. rapae eggs	3	0.43	0.5784
B. brassicae colonies	3	38.68	**0.0249**

4.7 Discussion

4.7.1 Lepidopteran pests: *Plutella xylostella* (diamondback moth) and *Pieris rapae* (cabbage white butterfly)

The presence of cereal rye in the cover crop treatments led to significant reductions in the number of *P. xylostella* eggs and subsequent larvae and pupae when compared to bare soil treatments. The reduction in *P. xylostella* numbers appeared very early in the development of the broccoli plants and is most likely related to the differences in the relative

distributions of *P. xylostella* eggs oviposited across the treatments. There were slight reductions in the number of *P. xylostella* larvae when the strip cropping treatments were compared to the Bare soil/Monoculture (conventional practice) at 22, 36 and 44 DAT in the 05/06 experiment, but these differences were not consistent across years and were minimal in comparison to the differences between the cover crop treatments and the bare soil treatments. In comparison to *P. xylostella*, the numbers of *P. rapae* eggs and larvae were relatively consistent across the treatments, which resulted in a more even distribution of *P. rapae* larvae and very few significant differences between treatments. The distinct differences between the relative numbers of eggs and larvae of both *P. xylostella* and *P. rapae* in cover crops and bare soil treatments was further supported by data from the semi-commercial trial.

If the reduced number of *P. xylostella* eggs in the cover crop treatments were due to egg predation (in line with the "enemies hypothesis" of Root [1973]) then it would be expected that the same effect would also be acting on the *P. rapae* egg numbers, as they are known to suffer high levels of egg predation (Schmaedick and Shelton 1999). Although predation of *P. rapae* eggs was not assessed, *P. xylostella* egg predation was, and unlike the *P. xylostella* egg data collected from the destructive samples, there were no distinct differences between the cover crop and bare soil treatments. These two pieces of information suggest that the low number of *P. xylostella* eggs in the cover crop treatments was due to fewer eggs being oviposited.

There is other evidence that *P. xylostella* oviposition can be negatively affected by cover crops, as previous research on other Brassica crops and cereal cover crop mixtures by Bukovinszky *et al.* (2004) found that number of both *P. xylostella* larvae and pupae were significantly reduced in barley-brussels sprouts intercrops. Mangan *et al.* (1995) and Mwaja *et al.* (1996) found fewer *P. xylostella* larvae on cabbages grown with cover crops, including cereal rye, when compared to conventional tillage. Bukovinszky *et al.* (2005) suggested that a barley background decreased the linear dimensions of plant patches so that plants no longer "loomed up" from the background, hence altering the perception of dimensional visual and olfactory cues. Furthermore, greater complexity with an extra

vegetational background in the cover cropping treatments might have made the *P. xylostella* lose host plants (Bukovinszky *et al.* 2005) or caused insects to alight "inappropriately" (Finch and Collier 2000) interfering with host location or host acceptance. The experiments detailed in this chapter cannot determine if the reductions in *P. xylostella* egg numbers were due to host location difficulties or reductions in oviposition due to interference with host acceptance behaviour. However, the most likely cause is interference with host location, as Finch and Collier (2000) suggest that *P. xylostella* adult females do not require much stimulus to oviposit and are likely to lay an egg on the first host plant encountered.

Replacing dead rye with living cover crops (that is, living mulches) may not necessarily lead to a reduction in *P. xylostella* numbers. Finch and Kienegger (1997) showed in a study of eight Brassica pest species (including *P. rapae*) that *P. xylostella* was affected the least by live clover backgrounds. This is supported by the experiment in 04/05 where an attempt was made to mimic a living mulch by painting the dead rye cover crop green but this did not result in any significant differences in insect numbers.

Another possible explanation of the reduction in *P. xylostella* numbers is that the cover crop caused a decline in crop growth and hence host plant attractiveness (Theunissen 1994), as plants in the cover crop treatments were slower growing and therefore smaller at any given time (Chapter 5). Conversely, *P. rapae* have a limited ability to discern host plant quality as they will oviposit on plants already laden with eggs and larvae, or plants that are stunted or have lower concentrations of nitrogen (Root and Kareiva 1984). However, results from trap crop choice tests show that leaf area, leaf shape and plant architecture appear not to be major factors in determining *P. xylostella* oviposition preferences (Badenes-Perez *et al.* 2004). Furthermore the oviposition leaf choice tests performed in the adult moth cage in the glasshouse did not provide any evidence of oviposition preferences across the treatments.

Another factor could be the sulphur content of the plants as the sap tests performed on the different treatments indicated that there was less sulphur in the cover crop broccoli plants

(Chapter 5), which has been shown to reduce *P. xylostella* oviposition (Marazzi *et al.* 2004; Marazzi and Stadler 2004). However, these published experiments compared the extreme situation of plants grown without sulphur to normally fertilised plants or plants with excess sulphur nutrition and are not supported by results from the laboratory population oviposition experiment. Experiments have also shown that different sulphur fertilisation rates have no significant effect on glucosinolate concentrations in broccoli inflorescences (Vallejo *et al.* 2003) and that glucosinolates are the stimulus for oviposition in *P. xylostella* (Reed *et al.* 1989).

The *P. rapae* results obtained from the 04/05 and 05/06 experiments are in agreement with Masiunas *et al.* (1997) who found no significant difference in the presence of *P. rapae* when comparing cabbages grown using conventional tillage (bare soil) or cereal rye cover crops. In general, *P. rapae* are reported to have the ability to precisely identify cruciferous plants (Root and Kareiva 1984) and are not affected by scales of landscape fragmentation (Banks 1998) or intercropping (Theunissen and den Ouden 1980). Unlike other Lepidopteran pests such as *P. xylostella*, *P. rapae* have been shown to have a significant negative relationship between plot size and the number of eggs laid per plant (Cromartie 1975; Bukovinszky *et al.* 2005), regardless of plant size, time of year or background (Cromartie 1975). Possibly due to host plant deprivation leading to gravid *P. rapae* females having higher motivation to oviposit more eggs on each plant successfully located in a patchy environment (Hern *et al.* 1996). Root and Kareiva (1984) describe the ovipositing behaviour of *P. rapae* as a Markovian process, which leads to an almost random spread of eggs on plants in a wide area. Root and Kareiva (1984) theorised that the egg spreading behaviour of an adult *P. rapae* female is an adaptive response that spreads the risk of her offspring's deaths among several plants. Furthermore, *P. rapae* butterflies in Australia have been found to spread their eggs more widely than *P. rapae* butterflies in Canada and the UK (Hern *et al.* 1996). All these factors lead to cover crops being an ineffective strategy in the control of *P. rapae*. This finding does not support assertions made by Potting *et al.* (2005) who expected that diversification strategies would be more effective on more highly mobile insect herbivores with directed flights and good sensory abilities that enable

oriented movements. However, these assertions were based on simulations and not field experiments.

Strip cropping dispersed two rows of broccoli plants amongst rows of potatoes (Potato strips treatments in 04/05 and 05/06) or standing rye (Rye strips treatment in 05/06), which in effect reduced the patch size of the broccoli stands. This field fragmentation had no significant affect on the number of *P. xylostella* larvae and pupae or *P. rapae* larvae. The *P. xylostella* results are in agreement with Bukovinszky *et al.* (2005) who found that *P. xylostella* larvae and pupae numbers were not affected by patch size. In the case of *P. rapae*, the failure of strip cropping could be related to greater perimeter to area ratios compared to the monocultures, meaning that *P. rapae* were more likely to "find" strips though increased encounter rates (Bukovinszky *et al.* 2005). This theory agrees with Root (1973) who found that on 88% of sampling occasions *P. rapae* abundance was greater in perimeter rows than in pure stands and only during population peaks was abundance higher in the pure stands compared to the perimeter rows.

There is no evidence that potatoes are an alternative host to the members of the Brassica pest complex. Therefore, broccoli strip cropping might be a more successful practice in the reduction of insect pests, if potatoes were replaced with a trap crop that is more attractive to insect pests either preventing them from reaching the crop, or concentrating them in an area where they can be chemically controlled (Hokkanen 1991). Alternatively, yellow rocket (*Barbarea vulgaris* var. *arcuata*) may provide a more attractive alternative host to the pest, and has the added benefit of not sustaining the development of *P. xylostella* larvae (Badenes-Perez *et al.* 2004). However, caution must be applied as not all purported trap crops are consistently effective. In a study of cabbage plots with Indian mustard (*Brassica juncea*) borders as trap crops by Luther *et al.* (1996) found no statistical differences in the presence of *P. xylostella* larvae or pupae. Another factor to consider is the economics of trap cropping, as replacing a percentage of a commercial crop with a trap crop might be appropriate from an insect control perspective but may not be financially viable.

4.7.2 *Brevicoryne brassicae* (cabbage aphid)

In all the experiments, including the semi-commercial trial, there were significantly fewer *B. brassicae* in the cover crop treatments than the bare soil treatments. Lower numbers of *B. brassicae* in cover crops and living mulches has been previously described (Tukahirwa and Coaker 1982; Costello 1994; Costello 1995; Theunissen *et al.* 1995; Vidal 1997). Aphids are known to locate plants using the contrast between the plant and the soil background to guide them (Doring *et al.* 2004). The cover crop could have acted as an optical competitor reducing the contrast between the background and the green host plant inducing an "inappropriate" landing (Finch and Collier 2000) on the cereal rye. Furthermore, upon alighting on a cover crop, the surface encourages probing activity that in turn induces a host rejection response (Doring *et al.* 2004), which induces the insect to leave the patch in much the same fashion as Finch and Collier (2000)'s appropriate/inappropriate landing theory. Alighting on soil does not induce probing and the aphid will walk or fly towards a green target (Doring *et al.* 2004). However, cover crops only appear to be an effective strategy when the background vegetation is dense compared to the host plant (Theunissen and den Ouden 1980; Tukahirwa and Coaker 1982), which can help to explain the observed increase in the number of alate *B. brassicae* and colonies over time. As the broccoli plants grew they occupied a greater area and thus reduced the contrast between the cover crop background and the broccoli plants. This in turn could have increased the colonisation rates of alate *B. brassicae* from outside the trial area by improving the likelihood of an "appropriate" landing on the host plant (Finch and Collier 2000). Another explanation for the increase in the numbers of aphids in the cover cropping treatments might simply be the ability of a few *B. brassicae* colonisers to rapidly increase numbers by producing fast developing live young from unfertilised eggs.

In the 04/05 experiment, there were initially more aphid colonies in the Bare soil/Potato strips treatment than the monoculture treatment. The same trend was also evident in the colonisation rates by alate *B. brassicae* in the 05/06 experiment, indicating that when the broccoli plants are small, the potato strips may orient flying alate aphids along these rows making them more likely to locate broccoli plants in between potato plants. However, analysis of the aphid colony distribution in 05/06 showed that *B. brassicae* numbers were

likely to be higher in the Bare soil/Monoculture than both the bare soil strip cropping treatments. These conflicting results can also be found in other published studies. Bukovinszky *et al.* (2005) found that *B. brassicae* densities were independent of patch size due to them being contact searchers with low maximum flight speeds and a strong arrestment response, making them unlikely to actively travel once a host plant is located. Banks (1998) found that all tested scales of landscape fragmentation negatively affected *B. brassicae* densities. Potting *et al.* (2005) agrees with Bukovinszky *et al.* (2005), finding that in simulations very small alate insects (like aphids) would be the most difficult pests to control with a diversification strategy as they have an airborne colonisation pattern, limited host detection ability and slow displacement speed. However, results from both Bukovinszky *et al.* (2005) and Potting *et al.* (2005) do not explain the observed differences between the cover crop and bare soil treatments as colonisation by chance alone should result in the consistent colonisation trends of treatment groups reported here.

4.7.3 Parasitism Rates

There were no significant differences in the parasitism rates of *P. xylostella* in 04/05 or 05/06. The pupal data from 05/06 showed that every *P. xylostella* pupae collected was parasitised. The data did not indicate that parasitoids in the experiment were less able to locate their target species in mixed cropping situations where there are also fewer individuals. This agrees with Bukovinszky *et al.* (2005) who found that parasitism rates of *P. xylostella* by *Diadegma* spp. were not affected by patch size or vegetation background. Complete parasitism of pupae in 05/06 could possibly explain the reduction in adult moth numbers over the course of the experiment as each parasitised *P. xylostella* larva or pupa results in the recruitment of a parasitic wasp into the next generation and not a moth. This directly reduces moth numbers and increases parasitism (Hamilton *et al.* 2004).
These high rates of parasitism can have major implications to the number of *P. xylostella* in a cropping system, as they have a relatively short life cycle, which under Australian conditions leads to a number of generations per season (Mo *et al.* 2003).

In both the 04/05 and the 05/06 experiment *B. brassicae* parasitism rates by *Diaeretiella rapae* appeared to be related to the relative numbers present in each treatment, rather than

the presence or absence of a cover crop. This finding is in agreement with Bukovinszky *et al.* (2005) who found that vegetational background did not influence parasitism of *B. brassicae*. Vidal (1997) found that parasitism of *B. brassicae* by *D. rapae* was only slightly decreased by intercropping with rye grass (*Lolium perenne*). Results from experiments with the green peach aphid (*Myzus persicae*) found no significant difference between conventional tillage (bare soil) and cereal rye cover crops (Masiunas *et al.* 1997), while Bukovinszky *et al.* (2004) found that the presence of natural enemies did not contribute to differences in *B. brassicae* densities in Brussels sprouts intercropped with barley (*Hordeum vulgare*).

4.8 Conclusions

The reduction in the number of *P. xylostella* and *B. brassicae* in the cover crop treatments support the assertion that a reduction in contrast provided by the cover crop background vegetation caused more of the landings to be "inappropriate" (Finch and Collier 2000) resulting in insects losing the target plants or interfering with host acceptance behaviour (Bukovinszky *et al.* 2005). Therefore lower densities of eggs, larvae and pupae of *P. xylostella* and alate *B. brassicae* and *B. brassicae* colonies in the rye cover crop treatment compared to the other treatments were most likely due to a different rate of colonisation (Finch and Kienegger 1997) and not parasitism or predation.

A possible evolutionary mechanism for the *P. xylostella* and *B. brassicae* results could be the co-development of the plants and their pest complexes as Brassicas developed in a niche provided by unstable land surfaces and are accustomed to growing in bare broken ground. Therefore, insect pests of Brassica crops would also presumably be adapted to finding plants in bare ground situations and not amongst background vegetation (Kostal and Finch 1994) including cover crops. However, this theory does not account for the behaviour of *P. rapae*, which was presumably also exposed to the same evolutionary mechanisms and yet the results presented here illustrate that the cover crop had no significant effect.

All the insect data indicated that there were no significant pest control benefits that could be derived from strip cropping. This is in spite of strip cropping Brassica plants with non-

host plants increasing the “clumpiness” of vegetation and fragmentation (Hern *et al.* 1996). This suggests that host plant location is not influenced by the presence of potatoes or the patchiness of the strip cropping treatments when compared to the monoculture treatments. These results suggest that insect plant discrimination operates at a smaller scale than a 1.65m strip, which contradicts the notions that mixed species cropping strategies, particularly strip cropping, could be important pest management tools in sustainable cropping systems (Rämert 2002).

Another factor to take into account when discussing the impact of plant diversity on herbivore behaviour, or making recommendations, is the need to clearly distinguish between different insects as to how active and perceptive they are (Banks and Ekbom 1999). *P. rapae*, with its highly developed visual and olfactory host location ability (Banks 1998), large size, daytime activity, Markovian movements (Root and Kareiva 1984) and very active egg spreading behaviour (Cromartie 1975; Root and Kareiva 1984; Hern *et al.* 1996; Bukovinszky *et al.* 2005) is not affected by increased plant species diversity in the cropping system. However, *P. rapae* are not a significant pest in Australia and relative to *P. xylostella* they are easier to control using insecticides.

Chapter 5 The impacts of a rye cover crop and strip crops on yield and quality of potatoes and broccoli

5.1 Introduction

The previous chapter demonstrated that a rye cover crop could result in significant reductions in the number of two commercially important pests in Australia. This chapter explores the agronomic effects of the rye cover crop and strip cropping on crop growth, yield, quality and gross margins from experiments conducted in the summers of 04/05 and 05/06.

5.2 Methodology

The experimental designs, sampling structures and planned contrasts of the analysis described in this chapter are the same as those described in Chapter 4. To avoid repetition only the methods that are specific to this chapter will be detailed.

5.2.1 Potato cover crop treatment planting and management 04/05

The establishment of the potato cover crop treatments in 04/05 differs from that of the other potato treatments discussed in Chapter 4. The potato cover crop treatments were pre-moulded into two ridges per 1.65m bed on 7 September 04. Cereal rye was then hand broadcast onto the moulds at the same rate as the broccoli cover crop treatments, with 100kg/ha of seed and 50kg/ha of fertiliser (14N:16P:11K). The moulds were then hand raked to cover the seed. The potatoes in the cover crop treatments were planted into the standing rye on 4 November 04, on the same day as potatoes in the other treatments using the same equipment. The planting process significantly suppressed the cover crop (Picture 5.1). On 2 December the cover crop was killed and weeds were controlled in all potato treatments with an application of Sprayseed® (paraquat 0.189kg a.i./ha and diquat 0.161kg ai/ha).

Picture 5.1. Potato Cover crop/Monoculture after planting 04/05.

5.2.2 Potato yield and quality assessment 04/05

In the 04/05 experiment, all the potatoes from each plot, except the outermost plot edge (guard) rows, were lifted to the surface with a twin row potato digger and bagged by hand (Picture 5.2). Potato yields were assessed as entire plot yields. Two approximately 20kg samples from each plot were graded for size and quality (as per Chapter 3). The quality parameters included the weight ranges of 850g-250g tubers (Large); 250g-75g tubers (Medium); and under 75g tubers (Small); as well as the percentage of tubers meeting the 'Bonus' category for both size and quality (for example free of bruising); and the total potatoes rejected for defects (Rejects).

Picture 5.2. Digging (left) and bagging (right) potatoes from the 04/05 experiment.

5.2.3 Broccoli yield assessment 04/05

For the 04/05 experiment, the broccoli harvest was conducted at four dates from 66 DAT until 76 DAT. There were 150 inflorescences (heads) harvested from each treatment in each Block. The heads were harvested by hand with a knife when they reached a marketable size or when they were becoming soft and would not be marketable at the next harvest.

Immediately after the final harvest, five plants from each treatment in each Block (minus the heads) were destructively sampled. Each plant was weighed and then divided into leaf and stem components. Time constraints meant that only fresh weights were assessed. A sub sample of leaf from each treatment in each Block was also run through a planimeter in order to determine leaf area index (LAI).

5.2.4 Broccoli plant sampling procedure 05/06

Immediately after the insect data collection activities were complete (Chapter 4), leaf and branch number counts of the same destructively harvested broccoli plants counts were taken. The plants were then checked for floral initiation as per Tan *et al.* (1998) and then partitioned into leaf and stem components, which were then oven dried at 75^{o}C for at least 48 hours and weighed. After floral initiation, the diameter of the inflorescence was also measured at each subsequent sampling date.

Sap based nutrient analysis using Nu-Test® (Serve-Ag Pty Ltd, Devonport, Tasmania) was performed at three different growth stages, namely 40% of final plant size (20 January 06), buttoning (6 February 06) and 30% of expected head diameter (20 February 06). At each sample, the youngest fully expanded leaf petiole and mid rib was taken from three randomly selected plants from each plot. The samples were then pooled into the six treatments. The procedure was completed before 8 am on the day of sampling and the samples were taken immediately to the lab for analysis. Samples were analysed for concentrations of nitrogen, phosphorous, potassium, calcium, magnesium, zinc, boron, sulphur, copper, iron, manganese, sodium and molybdenum.

5.2.5 Broccoli yield and quality assessment 05/06

In the 05/06 experiment, three plants were randomly allocated for yield assessment and these could be identified by a long white stick placed in the ground next to them (Picture 5.3). The plants were assessed for harvest suitability six times between 64 DAT until 76DAT. When the inflorescence reached a marketable size it was harvested with a knife, weighed and assessed for quality. The marker was then removed and placed in the ground at the end of the strip to ensure that all the designated plants within the strip were harvested. Quality was assessed on a scale of 1 to 5 score for head shape and branching angle, where "5" was the highest quality and "1" the lowest (Picture 5.4 from Tan *et al.* [1999]). Scores of 1 and 2 were considered unmarketable (Tan *et al.* 1999). The harvested heads were rated for hollow stem on a scale of 1 to 4 (modified from O'Donnell *et al.* [1998]), where "4" equated to no hollow stem, "3" to a trace of hollow stem, "2" to minor hollow stem and '1" to severe hollow stem (Picture 5.5).

Picture 5.3. A plant marked for harvest with a white stick.

Picture 5.4. Head shape – convex (5) to concave (1) (left) and branching angle tight (5) to spreading (1) (right) scales from (Tan *et al.* 1999).

Picture 5.5. Broccoli hollow stem scale with rankings in brackets (from left) – no hollow stem (4), trace (3), minor (2) and severe (1).

5.2.6 Data analysis 04/05 and 05/06

The potato and broccoli data from the 04/05 and the 05/06 experiments were analysed using one way ANOVA's in the same manner as the *P. xylostella* and *P. rapae* insect data, as discussed in Chapter 4.

5.3 Results

5.3.1 Potato yields 04/05

Potato yields were not significantly different across the four treatments (F=0.01, df=3, p=0.9561) and there was little variation between the plots (Table 5.1).

Table 5.1. Potato treatment yields 04/05.

Treatment	Number (n)	Mean weight per plot (kg) ± SE
Cover crop/Monoculture	3	386.87 ± 17.60
Cover crop/Broccoli strips	3	388.37 ± 12.56
Tilled soil/Monoculture	3	384.25 ± 3.56
Tilled soil/Broccoli strips	3	394.48 ± 12.73

When the harvested potatoes were assessed for quality, according to commercial specifications, the results were also not significant (Figure 5.1 and Table 5.2).

Figure 5.1. The percentage by weight of the 04/05 potato harvest allocated to each quality category ± SE

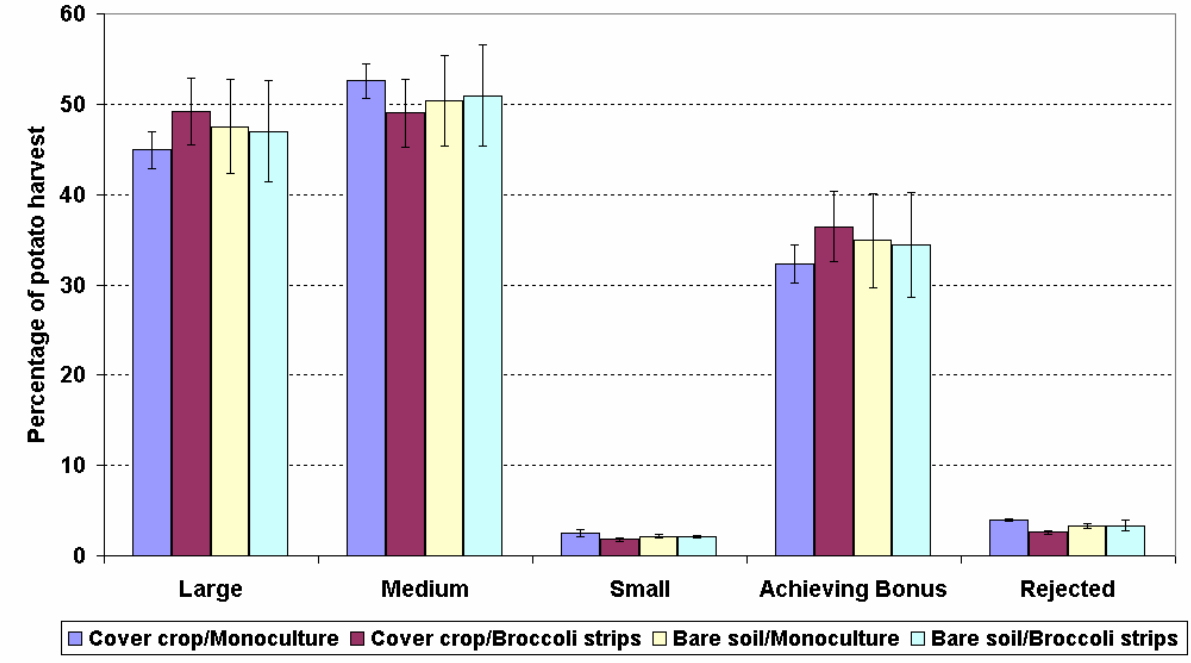


Table 5.2. The effect of treatment (four cropping systems) and planned comparisons of potato yield and quality in 04/05.

Total yield	***df***	***F***	***P***
Treatment	3	0.10	0.9561
Contrasts			
Cover crop v. Bare soil	1	0.02	0.9019
Strip v. Monoculture	1	0.28	0.6143
Large tubers	***df***	***F***	***P***
Treatment	3	0.21	0.8868
Contrasts			
Cover crop v. Bare soil	1	0.00	0.9673
Strip v. Monoculture	1	0.01	0.9258
Medium tubers	***df***	***F***	***P***
Treatment	3	0.16	0.9199
Contrasts			
Cover crop v. Bare soil	1	0.00	0.9702
Strip v. Monoculture	1	0.01	0.9159

Small tubers	***df***	***F***	***P***
Treatment	3	2.06	0.2070
Contrasts			
Cover crop v. Bare soil	1	0.00	0.9512
Strip v. Monoculture	1	0.03	0.8708
Tubers achieving bonus	***df***	***F***	***P***
Treatment	3	0.18	0.9037
Contrasts			
Cover crop v. Bare soil	1	0.00	0.9698
Strip v. Monoculture	1	0.01	0.9279
Rejected tubers	***df***	***F***	***P***
Treatment	3	2.13	0.1983
Contrasts			
Cover crop v. Bare soil	1	0.01	0.9304
Strip v. Monoculture	1	0.00	0.9810

Due to the absence of any significant treatment differences, potatoes were subsequently considered only as a potential strip crop with broccoli in the 05/06 experiment and were not assessed for yield or quality.

5.3.2 Broccoli growth and development 04/05

Partitioned crop data collected as fresh weights from the 04/05 experiment after the last harvest, show significant treatment differences in leaf area (Figure 5.2 and Table 5.3). Broccoli plants from the cover cropping treatments had significantly smaller leaves than plants from the bare soil treatments and this was also reflected in the similar proportional differences in the leaf weights. Additionally, there were also significant treatment differences in green stem biomass results. The pairwise contrast of the cover crop and bare soil treatments was significant, as were the cover crop and bare soil contrasts for leaf area and leaf weight. These results, on balance, indicate that the bare soil treatments accumulated more above ground biomass and had greater leaf area than the cover crop treatments.

Figure 5.2. Mean broccoli plant partitioning results from 04/05 ± SE, ns" not significant; * $P \leq 0.05$; ** $P \leq 0.01$. Individual columns within each group without a letter in common are significantly different (P=0.05).

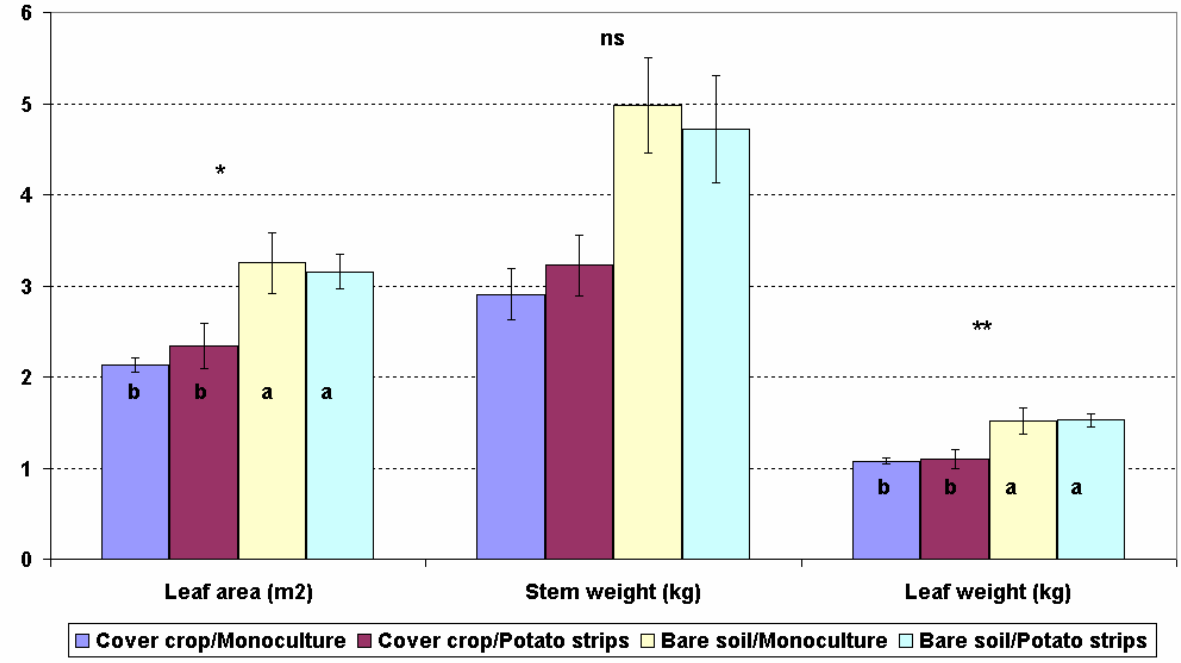


Table 5.3. The effect of treatment (four cropping systems) and planned comparisons of broccoli leaf area and plant biomass in 04/05. Significant results are shown in bold type.

Broccoli leaf area	***df***	***F***	***P***
Treatment	3	5.87	**0.0323**
Contrasts			
Cover crop v. Bare soil	1	17.12	**0.0061**
Strip v. Monoculture	1	0.06	0.8102
Broccoli stem weight	***df***	***F***	***P***
Treatment	3	4.16	0.0651
Contrasts			
Cover crop v. Bare soil	1	12.15	**0.0131**
Strip v. Monoculture	1	0.00	0.9579
Broccoli leaf weight	***df***	***F***	***P***
Treatment	3	11.64	**0.0065**
Contrasts			
Cover crop v. Bare soil	1	34.87	**0.0010**
Strip v. Monoculture	1	0.06	0.8175

Data collected for the number of days from transplanting to harvest show that the bare soil treatments developed significantly faster (4-5 days) than the cover crop treatments (Figure 5.3 and Table 5.4). As a result the pairwise contrast of the cover crop and bare soil treatments was also significant, while there was no difference between the strip cropping and monoculture treatments.

Figure 5.3. The mean number of days from transplanting to harvest in 04/05 ± SE. Treatments without a letter in common are significantly different (*P*=0.05).

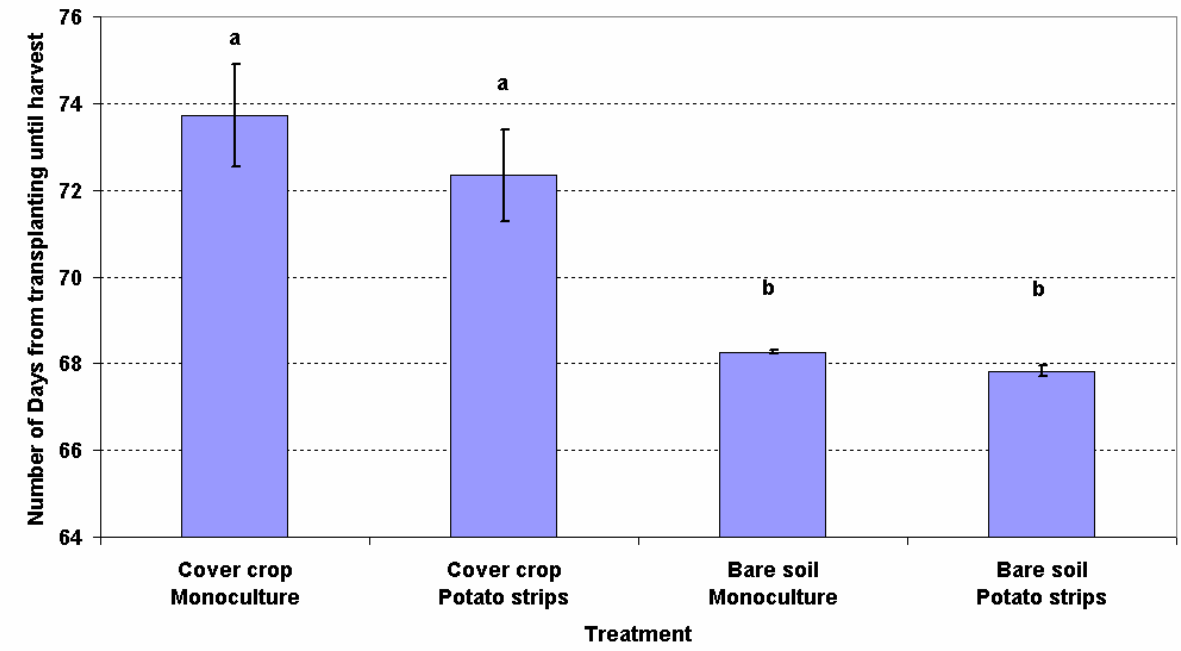


Table 5.4. The effect of treatment (four cropping systems) and planned comparisons of the number of days from transplanting to harvest in 04/05. Significant results are shown in bold type.

Analysis	*df*	*F*	*P*
Treatment	3	10.46	**0.0085**
Contrasts			
Cover crop v. Bare soil	1	30.12	**0.0015**
Strip v. Monoculture	1	1.00	0.3563

5.3.3 Broccoli yield and quality 04/05

The broccoli yield results from the 04/05 experiment suggest that the cover crop treatments produced lower average head weights than the bare soil treatments. While this was not a statistically significantly result, it is in line with trends in the biomass partitioning and leaf

area results (Figure 5.4 and Table 5.5). The pairwise contrast of the cover crop treatments and the bare soil treatments were also not significant.

Figure 5.4. Broccoli mean harvested head weights in 04/05 ± SE.

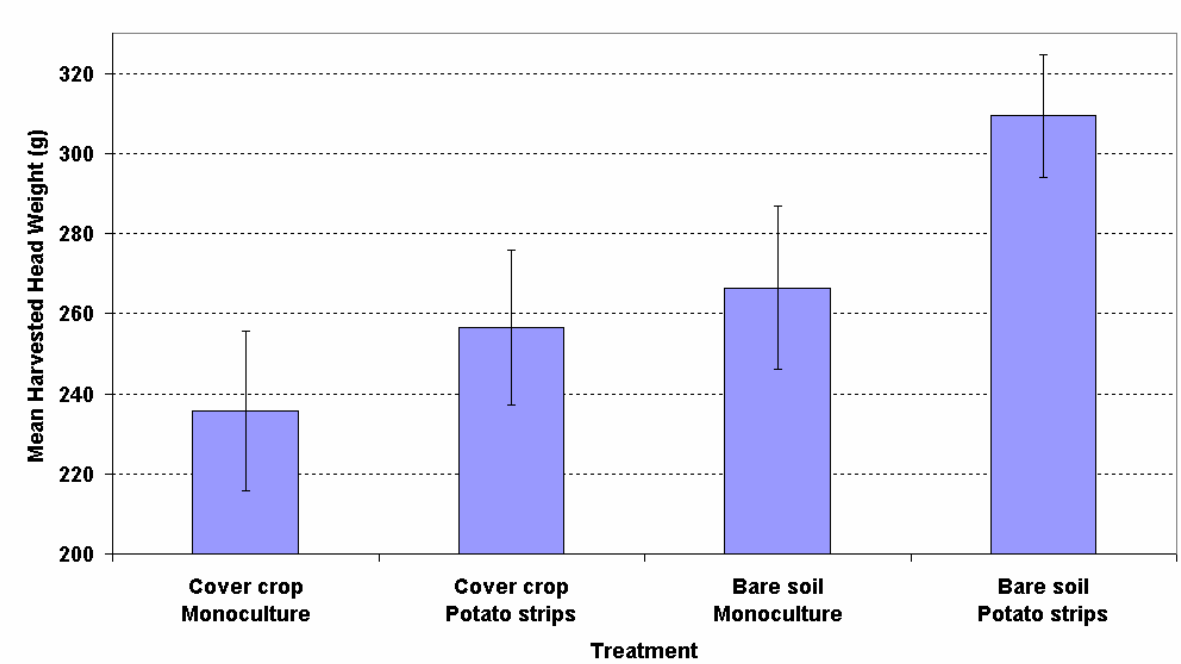


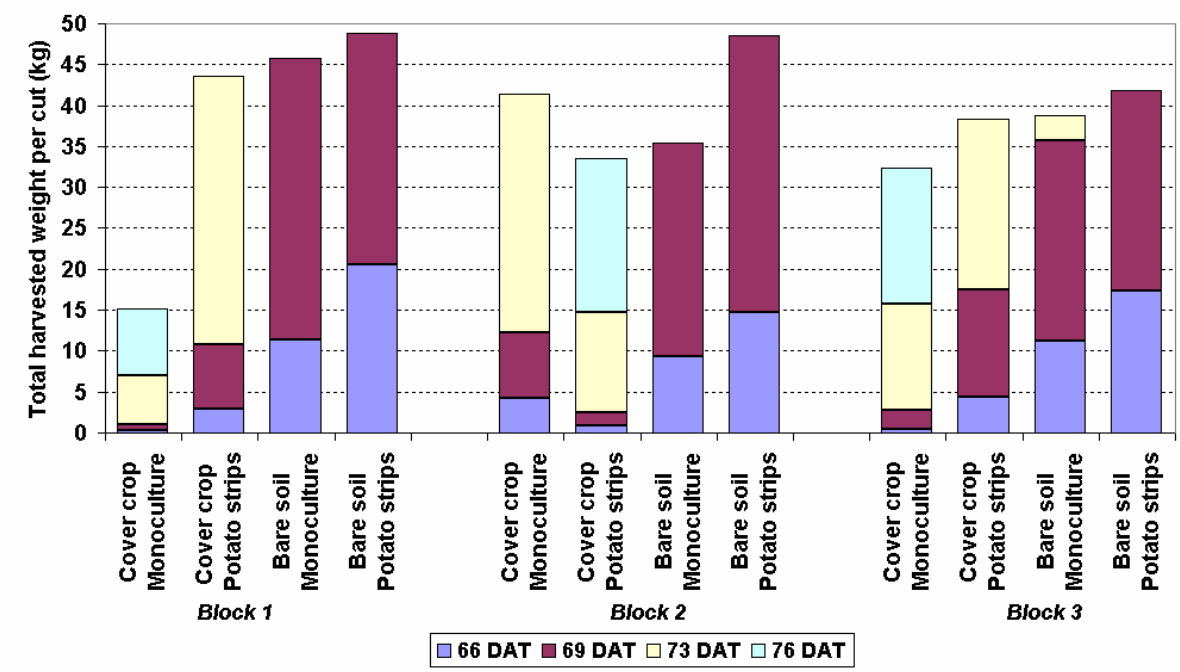
Table 5.5. The effect of treatment (four cropping systems) and planned comparisons of harvested head weight per plant in 04/05. Significant results are shown in bold type.

	df	*F*	*P*
Treatment	3	2.69	0.1398
Contrasts			
Cover crop v. Bare soil	1	2.84	0.1429
Strip v. Monoculture	1	4.88	0.0692

The total accumulated yield for each plot indicates that there was significant variation between the blocks, which reduced the likelihood of significant treatment differences (Figure 5.5). The Cover crop/Monoculture treatment in Block 1 had a very low yield. This was due to early establishment problems caused by a blocked sprinkler, resulting in only 70 harvestable heads of poor quality. Removing this data from the analysis did not result in a statistically significant difference. Although not a significant result, the Bare soil/Potato strips treatment had the greatest accumulated yield in each Block. Furthermore, the harvest of the Bare soil/Potato strips treatment was completed in the fewest number of harvests

(two). This graph also indicates that the cover crop treatments were slower growing and required more harvests than the bare soil treatments.

Figure 5.5. Total combined broccoli yields per plot in 04/05. DAT=days after transplanting.



5.3.4 Broccoli growth and development 05/06

Analysis of the mean number of leaves per plant in the 05/06 experiment showed that there were very significant treatment differences at all but the first sampling date, with the bare soil treatments having approximately twice the number of leaves as the cover crop treatments (Figure 5.6 and Table 5.6). The pairwise contrasts of the cover crop and the bare soil treatments were significant at every sampling date with the first sample having a lower significance than the following six samples. The LSD's for the treatments indicate that there were no significant differences within the cover crop treatments from 22-59 DAT. Within the bare soil treatments, the Bare soil/Monoculture treatment had significantly more leaves than the other treatments at 36 and 52 DAT. However, at the final sample at 59 DAT the Bare soil/Rye strips treatment had the greatest number of leaves.

Figure 5.6. Mean number of leaves of broccoli plants in 05/06 ± SE. "ns" not significant; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

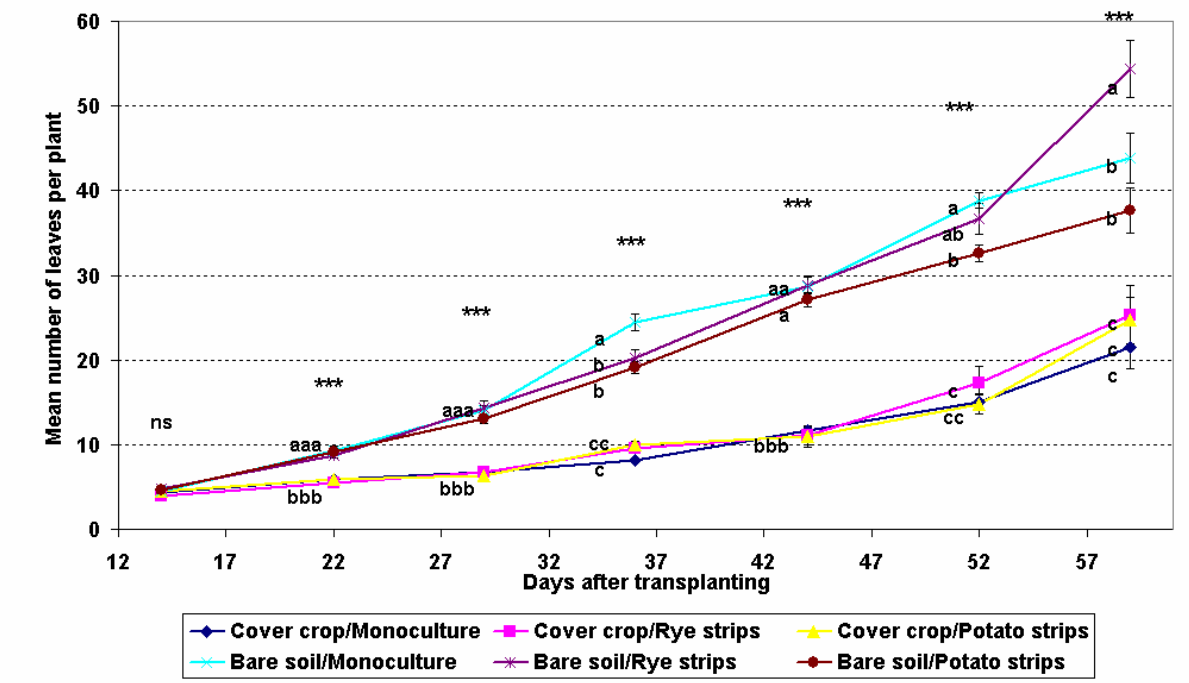


Table 5.6. The effect of treatment (six cropping systems) and planned comparisons of the number of leaves per plant in 05/06. Significant results are shown in bold type.

14 days after transplanting	***df***	***F***	***P***
Treatment	5	2.19	0.0955
Contrasts			
Cover crop v. Bare soil	1	4.97	**0.0374**
Strip v. Monoculture	1	0.14	0.7146
Bare soil strip v. Bare soil monoculture	1	1.53	0.2299
22 days after transplanting	***df***	***F***	***P***
Treatment	5	24.69	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	121.15	**<0.0001**
Strip v. Monoculture	1	0.74	0.4000
Bare soil strip v. Bare soil monoculture	1	0.72	0.4046

29 days after transplanting	***df***	***F***	***P***
Treatment	5	54.91	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	271.12	**<0.0001**
Strip v. Monoculture	1	0.33	0.5739
Bare soil strip v. Bare soil monoculture	1	0.22	0.6448
36 days after transplanting	***df***	***F***	***P***
Treatment	5	82.93	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	383.96	**<0.0001**
Strip v. Monoculture	1	5.74	**0.0265**
Bare soil strip v. Bare soil monoculture	1	26.43	**<0.0001**
44 days after transplanting	***df***	***F***	***P***
Treatment	5	112.10	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	557.87	**<0.0001**
Strip v. Monoculture	1	0.73	0.4026
Bare soil strip v. Bare soil monoculture	1	0.41	0.5274
52 days after transplanting	***df***	***F***	***P***
Treatment	5	68.98	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	332.31	**<0.0001**
Strip v. Monoculture	1	1.92	0.1812
Bare soil strip v. Bare soil monoculture	1	6.37	**0.0202**
59 days after transplanting	***df***	***F***	***P***
Treatment	5	19.39	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	79.57	**<0.0001**
Strip v. Monoculture	1	1.23	0.2797
Bare soil strip v. Bare soil monoculture	1	0.36	0.5547

The greater number of leaves in the bare soil treatments also meant that these treatments had greater leaf dry weights at each sampling date as illustrated by Figure 5.7 and Table 5.7, although the Bare soil/Potato strips treatment was not significantly different to all the

cover crop treatments from 44 DAT onwards. However, the pairwise contrasts of the cover crop and bare soil treatments were significant at all sampling dates. The sample dry weights also declined markedly between 52 and 59 DAT.

Figure 5.7. The log of total leaf dry weight per plant from 05/06 ± SE. * $P \leq 0.05$; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

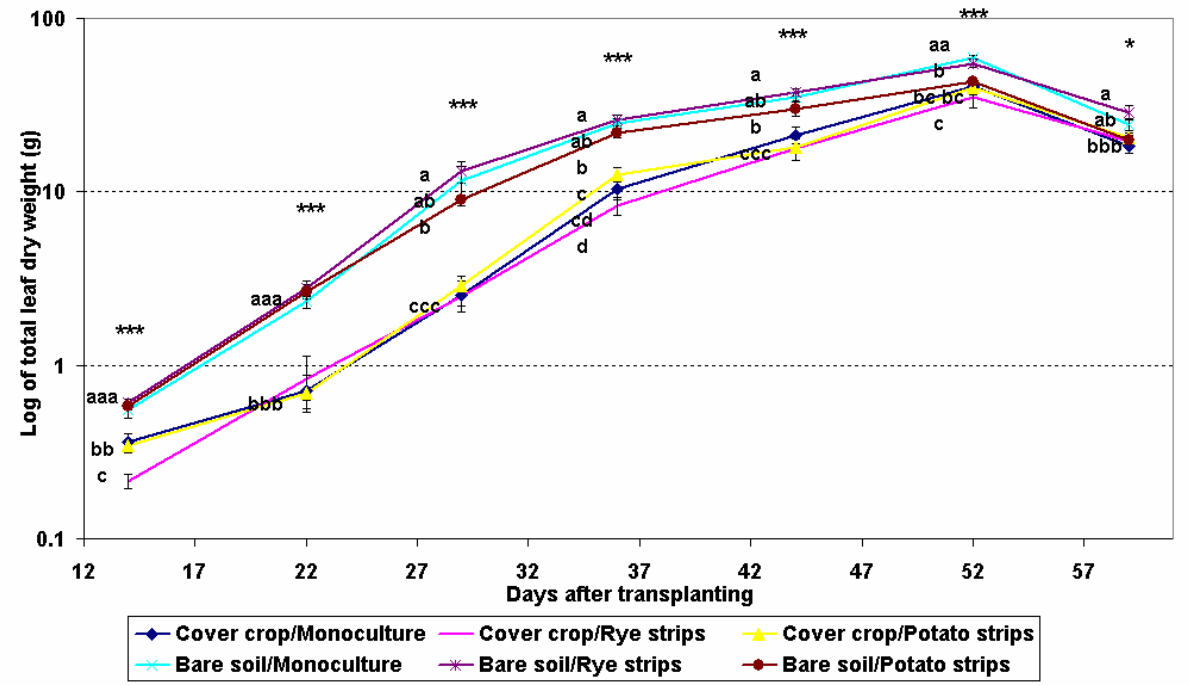


Table 5.7. The effect of treatment (six cropping systems) and planned comparisons of total leaf dry weight in 05/06. Significant results are shown in bold type.

14 days after transplanting	***df***	***F***	***P***
Treatment	5	18.44	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	81.74	**<0.0001**
Strip v. Monoculture	1	0.34	0.5692
Bare soil strip v. Bare soil monoculture	1	1.00	0.3290
22 days after transplanting	***df***	***F***	***P***
Treatment	5	28.93	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	141.41	**<0.0001**
Strip v. Monoculture	1	1.69	0.2079
Bare soil strip v. Bare soil monoculture	1	2.72	0.1147

29 days after transplanting	***df***	***F***	***P***
Treatment	5	19.45	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	89.93	**<0.0001**
Strip v. Monoculture	1	0.03	0.8660
Bare soil strip v. Bare soil monoculture	1	0.12	0.7344
36 days after transplanting	***df***	***F***	***P***
Treatment	5	39.40	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	185.71	**<0.0001**
Strip v. Monoculture	1	0.20	0.6573
Bare soil strip v. Bare soil monoculture	1	0.50	0.4862
44 days after transplanting	***df***	***F***	***P***
Treatment	5	18.36	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	83.58	**<0.0001**
Strip v. Monoculture	1	1.68	0.2092
Bare soil strip v. Bare soil monoculture	1	0.25	0.6222
52 days after transplanting	***df***	***F***	***P***
Treatment	5	12.37	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	40.66	**<0.0001**
Strip v. Monoculture	1	8.17	**0.0097**
Bare soil strip v. Bare soil monoculture	1	9.83	**0.0052**
59 days after transplanting	***df***	***F***	***P***
Treatment	5	3.33	**0.0237**
Contrasts			
Cover crop v. Bare soil	1	7.52	**0.0126**
Strip v. Monoculture	1	0.12	0.7342
Bare soil strip v. Bare soil monoculture	1	0.01	0.9085

When the leaf dry weights were expressed on a per leaf basis there were significant differences between the treatments at all sampling dates (Figure 5.8 and Table 5.8). However, the differences between the treatments changed with time as the cover crop treatment's leaves were lighter than the bare soil treatments until 29 DAT, then at 44 DAT

and thereafter they became heavier than the bare soil treatments. These data combined with that presented in Figure 5.6 and Figure 5.7, indicate that the cover crop treatments accumulated less leaf biomass and had fewer but heavier leaves when compared to the bare soil treatments. It should also be noted that the drop in leaf dry weight between 52 and 59 DAT was due to the senescence and detachment of the lower leaves.

Figure 5.8. Mean leaf dry weight in 05/06 ± SE. ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

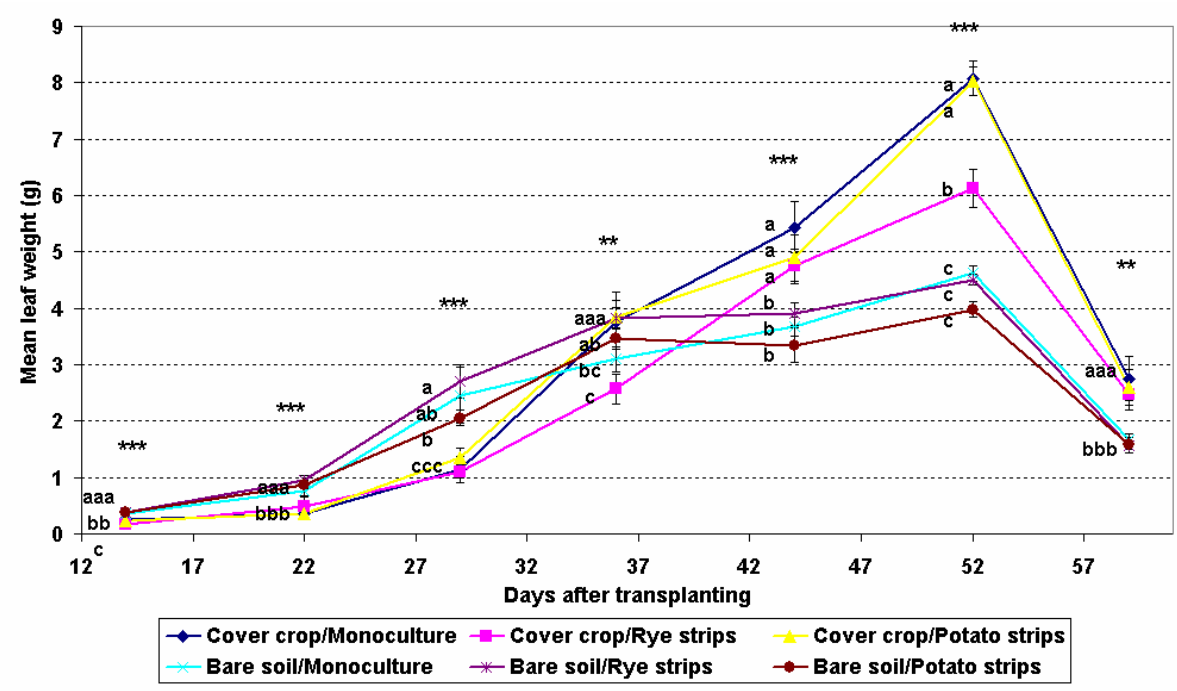


Table 5.8. The effect of treatment (six cropping systems) and planned comparisons of mean leaf dry weight per plant in 05/06. Significant results are shown in bold type.

14 days after transplanting	*df*	*F*	*P*
Treatment	5	28.28	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	128.18	**<0.0001**
Strip v. Monoculture	1	1.54	0.2286
Bare soil strip v. Bare soil monoculture	1	0.32	0.5755

22 days after transplanting	***df***	***F***	***P***
Treatment	5	12.42	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	58.69	**<0.0001**
Strip v. Monoculture	1	1.76	0.2001
Bare soil strip v. Bare soil monoculture	1	1.90	0.1830
29 days after transplanting	***df***	***F***	***P***
Treatment	5	12.32	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	55.33	**<0.0001**
Strip v. Monoculture	1	0.00	0.9820
Bare soil strip v. Bare soil monoculture	1	0.10	0.7533
36 days after transplanting	***df***	***F***	***P***
Treatment	5	4.74	**0.0051**
Contrasts			
Cover crop v. Bare soil	1	0.12	0.7351
Strip v. Monoculture	1	0.00	0.9748
Bare soil strip v. Bare soil monoculture	1	3.64	0.0708
44 days after transplanting	***df***	***F***	***P***
Treatment	5	10.12	<0.0001
Contrasts			
Cover crop v. Bare soil	1	43.94	<0.0001
Strip v. Monoculture	1	2.02	0.1711
Bare soil strip v. Bare soil monoculture	1	0.11	0.7391
52 days after transplanting	***df***	***F***	***P***
Treatment	5	61.65	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	258.10	**<0.0001**
Strip v. Monoculture	1	11.73	**0.0027**
Bare soil strip v. Bare soil monoculture	1	1.71	0.2063

59 days after transplanting	*df*	*F*	*P*
Treatment	5	4.82	**0.0047**
Contrasts			
Cover crop v. Bare soil	1	23.39	**0.0001**
Strip v. Monoculture	1	0.54	0.4721
Bare soil strip v. Bare soil monoculture	1	0.12	0.7335

Treatment trends in stem dry weight were similar to those for leaf dry weight, in that the bare soil treatments on average produced more stem biomass than the cover crop treatments (Figure 5.9 and Table 5.9). Like the leaf results, plants from the Bare soil/Potato strips treatment had significantly lighter stems than the other bare soil treatments, but higher stem weight than the cover crop treatments for all but the final sample. As per the leaf data, there was a drop in stem dry weight across treatments between 52 and 59 DAT as the lower leaves, petioles and midribs senesced and detached.

Figure 5.9. Log of mean stem dry weight 05/06 ± SE. *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

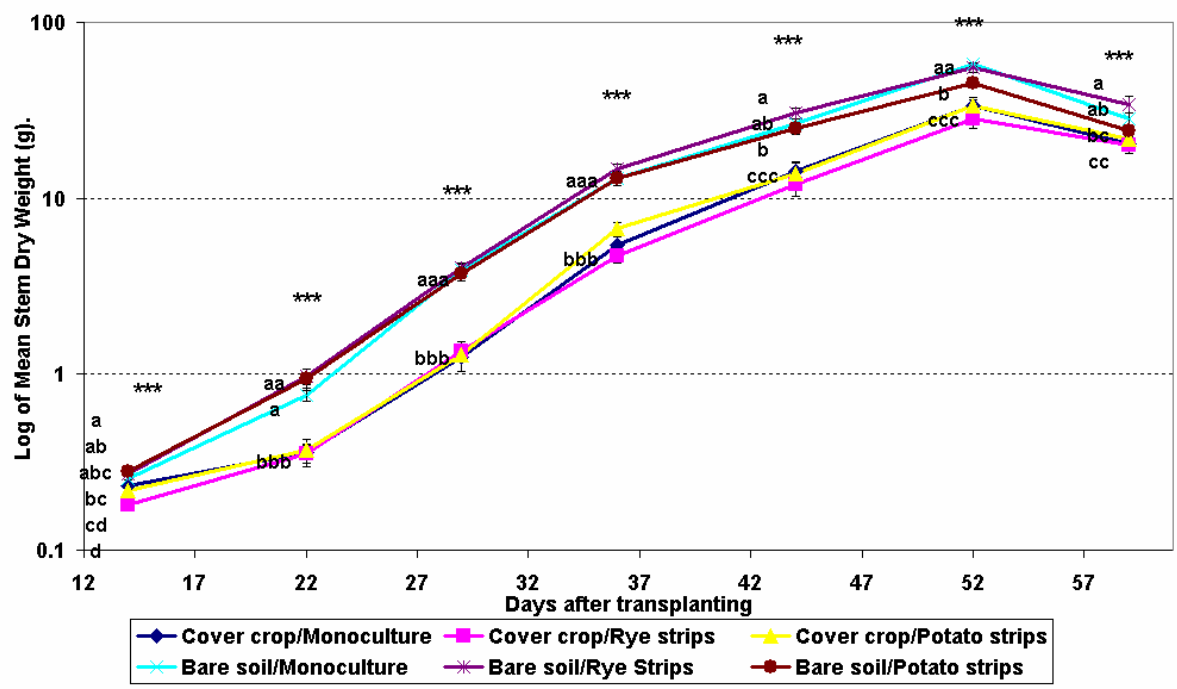


Table 5.9. The effect of treatment (six cropping systems) and planned comparisons of stem dry weight in 05/06. Significant results are shown in bold type.

14 days after transplanting	***df***	***F***	***P***
Treatment	5	8.04	**0.0003**
Contrasts			
Cover crop v. Bare soil	1	30.46	**<0.0001**
Strip v. Monoculture	1	0.36	0.5569
Bare soil strip v. Bare soil monoculture	1	1.50	0.2350
22 days after transplanting	***df***	***F***	***P***
Treatment	5	18.17	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	85.85	**<0.0001**
Strip v. Monoculture	1	2.50	0.1296
Bare soil strip v. Bare soil monoculture	1	4.85	**0.0395**
29 days after transplanting	***df***	***F***	***P***
Treatment	5	43.89	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	218.37	**<0.0001**
Strip v. Monoculture	1	0.01	0.9236
Bare soil strip v. Bare soil monoculture	1	0.02	0.8921
36 days after transplanting	***df***	***F***	***P***
Treatment	5	32.67	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	157.14	**<0.0001**
Strip v. Monoculture	1	0.65	0.4298
Bare soil strip v. Bare soil monoculture	1	0.62	0.4394
44 days after transplanting	***df***	***F***	***P***
Treatment	5	31.16	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	146.93	**<0.0001**
Strip v. Monoculture	1	0.02	0.8760
Bare soil strip v. Bare soil monoculture	1	0.31	0.5824

52 days after transplanting	*df*	*F*	*P*
Treatment	5	17.51	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	75.76	**<0.0001**
Strip v. Monoculture	1	3.44	0.0784
Bare soil strip v. Bare soil monoculture	1	3.86	0.0636
59 days after transplanting	***df***	***F***	***P***
Treatment	5	8.45	**0.0002**
Contrasts			
Cover crop v. Bare soil	1	27.97	**<0.0001**
Strip v. Monoculture	1	0.15	0.7012
Bare soil strip v. Bare soil monoculture	1	0.14	0.7146

Analysis of the number of major branches arising from (and including) the main stem indicates that the cover cropping treatments had significantly less additional branching than the bare soil treatments (Figure 5.10 and Table 5.10). Amongst the bare soil treatments the Bare soil/Potato strips treatment had significantly less additional branching at the later sample than the Bare soil/Monoculture and the Bare soil/Rye strips treatments.

Figure 5.10. Mean number of branches arising from and including the main stem ± SE. * *P* ≤ 0.001. Treatments in each group without a letter in common are significantly different (*P*=0.05).**

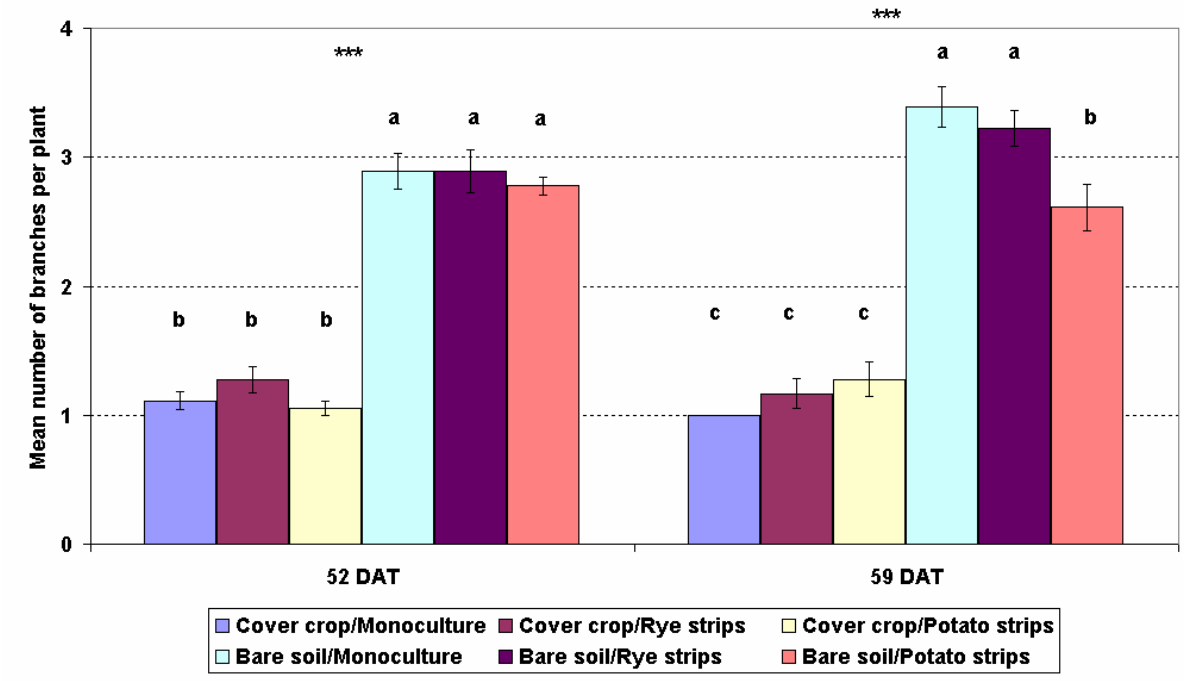


Table 5.10. The effect of treatment (six cropping systems) and planned comparisons of the number of branches per plant in 05/06. Significant results are shown in bold type.

52 days after transplanting	***df***	***F***	***P***
Treatment	5	86.18	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	427.47	**<0.0001**
Strip v. Monoculture	1	0.00	1.0000
Bare soil strip v. Bare soil monoculture	1	0.20	0.6579
59 days after transplanting	***df***	***F***	***P***
Treatment	5	52.71	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	246.94	**<0.0001**
Strip v. Monoculture	1	0.92	0.3477
Bare soil strip v. Bare soil monoculture	1	6.60	**0.0183**

When the stem lengths of the broccoli plants were assessed there were significant differences at each sampling date except at 44 DAT (Figure 5.11 and Table 5.11). The cover crop treatments typically had longer stems early in the season as they grew out of the cover crop. The sample taken 52 DAT indicated that plants from the Bare soil/Potato strips treatment became the longest as competition for light with the neighbouring potato plants strengthened. Up until the last sample the Bare soil/Monoculture treatment, which had the least competition for light, had the shortest stems of all treatments.

Figure 5.11. Mean stem length of broccoli plants from 05/06 ± SE. "ns" not significant; * *P* ≤ 0.05; ** *P* ≤ 0.01; * *P* ≤ 0.001. Points without a letter in common are significantly different (*P*=0.05).**

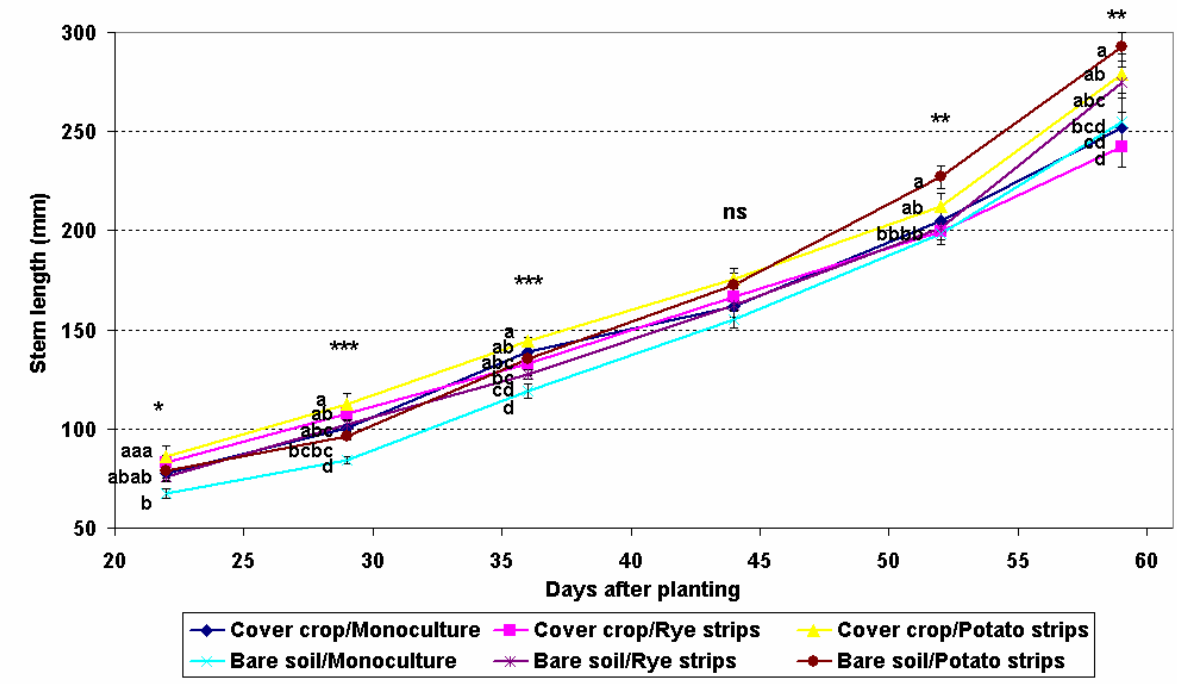


Table 5.11. The effect of treatment (six cropping systems) and planned comparisons of stem length in 05/06. Significant results are shown in bold type.

22 days after transplanting	***df***	***F***	***P***
Treatment	5	3.37	**0.0228**
Contrasts			
Cover crop v. Bare soil	1	8.48	**0.0086**
Strip v. Monoculture	1	7.44	**0.0130**
Bare soil strip v. Bare soil monoculture	1	5.10	**0.0352**
29 days after transplanting	***df***	***F***	***P***
Treatment	5	6.74	**0.0008**
Contrasts			
Cover crop v. Bare soil	1	16.57	**0.0006**
Strip v. Monoculture	1	14.36	**0.0011**
Bare soil strip v. Bare soil monoculture	1	10.39	**0.0043**

36 days after transplanting	***df***	***F***	***P***
Treatment	5	6.63	**0.0009**
Contrasts			
Cover crop v. Bare soil	1	16.52	**0.0006**
Strip v. Monoculture	1	4.16	0.0548
Bare soil strip v. Bare soil monoculture	1	8.82	**0.0076**
44 days after transplanting	***df***	***F***	***P***
Treatment	5	2.08	0.1100
Contrasts			
Cover crop v. Bare soil	1	1.11	0.3057
Strip v. Monoculture	1	5.72	**0.0267**
Bare soil strip v. Bare soil monoculture	1	3.74	0.0673
52 days after transplanting	***df***	***F***	***P***
Treatment	5	4.60	**0.0059**
Contrasts			
Cover crop v. Bare soil	1	0.60	0.4481
Strip v. Monoculture	1	3.48	0.0769
Bare soil strip v. Bare soil monoculture	1	6.38	**0.0201**
59 days after transplanting	***df***	***F***	***P***
Treatment	5	4.40	**0.0073**
Contrasts			
Cover crop v. Bare soil	1	4.80	**0.0404**
Strip v. Monoculture	1	5.69	**0.0270**
Bare soil strip v. Bare soil monoculture	1	6.53	**0.0188**

Monitoring of floral initiation at 36 DAT showed that plants in the Bare soil/Rye strips and the Bare soil/Potato strips treatments had commenced floral initiation in advance of other treatments (Table 5.12).

Table 5.12. Proportion of plants with initiated heads at 36 DAT ± SE.

Treatment	Mean ± SE
Cover crop/Monoculture	0.6111± 0.0691
Cover crop/Rye strips	0.3889 ± 0.0375
Cover crop/Potato strips	0.6111± 0.0375
Bare soil/Monoculture	0.8889± 0.0474
Bare soil/Rye strips	1 ± 0
Bare soil/Potato strips	1 ± 0

Significant differences in floral initiation were also evident in the diameter expansion rates of the broccoli heads, with the cover crop treatments developing at a slower rate than the bare soil treatments (Figure 5.12 and Table 5.13). The Bare soil/Potato strips treatment exhibited the most rapid rate of development and had the largest mean head diameter at 59 DAT. The Cover crop/Rye strips treatment was the slowest developing treatment, although it was not significantly different to the Cover crop/Monoculture treatment.

Figure 5.12. Mean head diameter development of broccoli plants in 05/06 ± SE. *** $P \leq 0.001$. Points without a letter in common are significantly different (P=0.05).

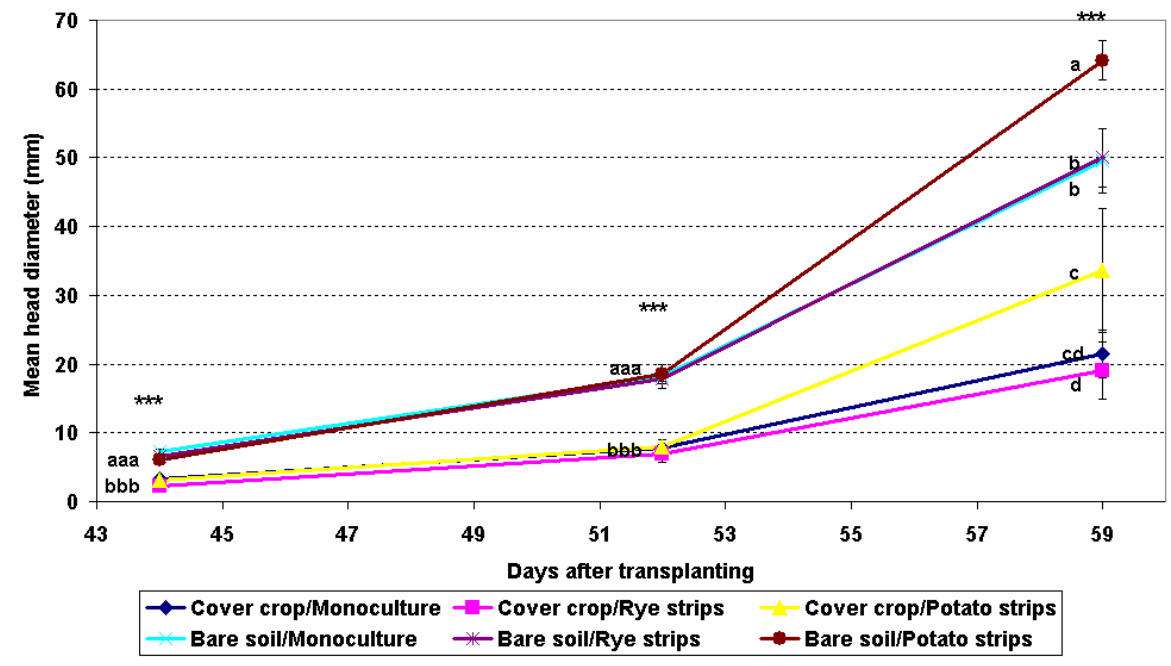


Table 5.13. The effect of treatment (six cropping systems) and planned comparisons of head diameter development in 05/06. Significant results are shown in bold type.

44 days after transplanting	***df***	***F***	***P***
Treatment	5	28.94	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	137.62	**<0.0001**
Strip v. Monoculture	1	4.30	0.0512
Bare soil strip v. Bare soil monoculture	1	2.98	0.0999
52 days after transplanting	***df***	***F***	***P***
Treatment	5	30.58	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	150.66	**<0.0001**
Strip v. Monoculture	1	0.14	0.7163
Bare soil strip v. Bare soil monoculture	1	0.01	0.9171
59 days after transplanting	***df***	***F***	***P***
Treatment	5	18.78	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	78.57	**<0.0001**
Strip v. Monoculture	1	2.99	0.0990
Bare soil strip v. Bare soil monoculture	1	2.22	0.1518

The number of days from transplant until harvest were similar in the 04/05 and the 05/06 experiment, with the cover crop treatments requiring approximately four to six days longer to develop, while the Cover crop/Rye strips treatment developed slower than all the other treatments (Figure 5.13 and Table 5.14). The faster development rate of the bare soil treatments compared to the cover crop treatment was also demonstrated by the very significant pairwise contrast.

Figure 5.13. The mean number of days from transplanting to harvest in 05/06 ± SE. Treatments without a letter in common are significantly different (*P*=0.05).

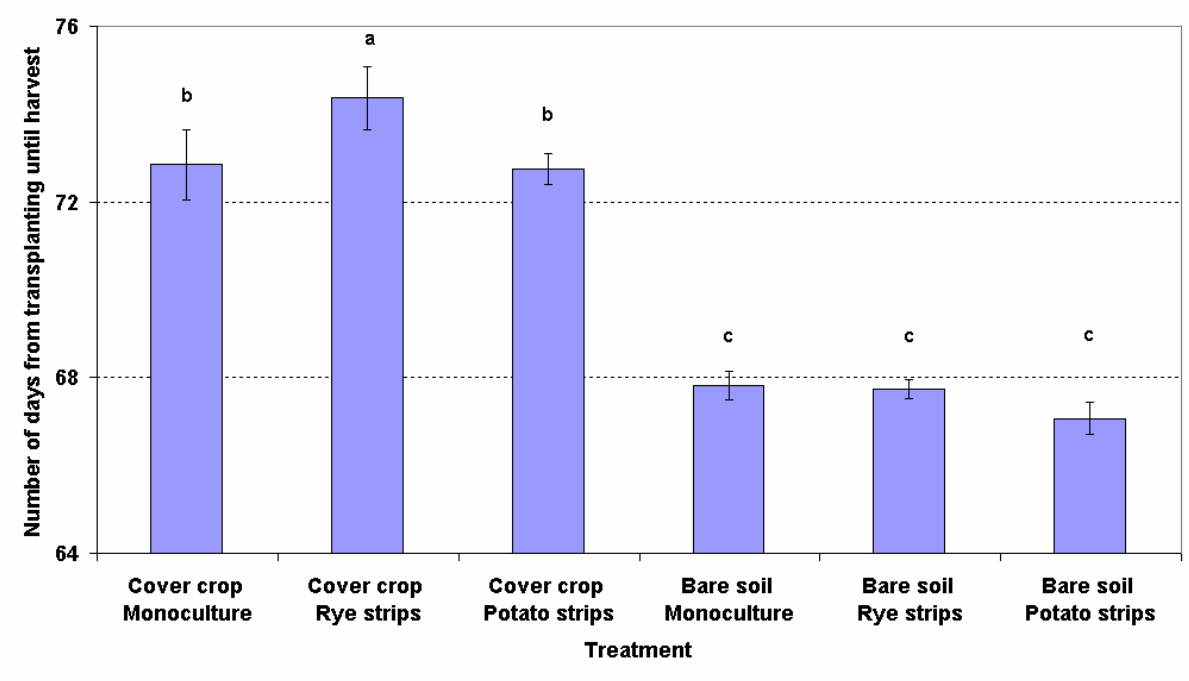


Table 5.14. The effect of treatment (six cropping systems) and planned comparisons of the number of days from transplanting to harvest in 05/06. Significant results are shown in bold type.

Analysis	*df*	*F*	*P*
Treatment	5	42.17	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	202.87	**<0.0001**
Strip v. Monoculture	1	0.13	0.7265
Bare soil strip v. Bare soil monoculture	1	0.45	0.5112

5.3.5 Broccoli yield and quality 05/06

The trend towards greater broccoli yields in the bare soil treatments compared to the cover crop treatments in the 04/05 experiment, was also evident in the 05/06 experiment, with the bare soil treatments producing heavier heads than the cover crop treatments (Figure 5.14 and Table 5.15). This difference was also apparent in the very significant pairwise contrast of the bare soil treatments and the cover crop treatments. There were also differences within the cover crop treatments, with the Cover crop/Rye strips treatment producing significantly smaller harvested heads than all other treatments including Cover

crop/Monoculture and Cover crop/Potato strips. However, there were no significant differences between the pairwise contrasts of strip crops and monocultures or the contrast of the two bare soil strip crops and the Bare soil/Monoculture.

Figure 5.14. Broccoli mean harvested head weights in 05/06 ± SE. Treatments without a letter in common are significantly different (*P*=0.05).

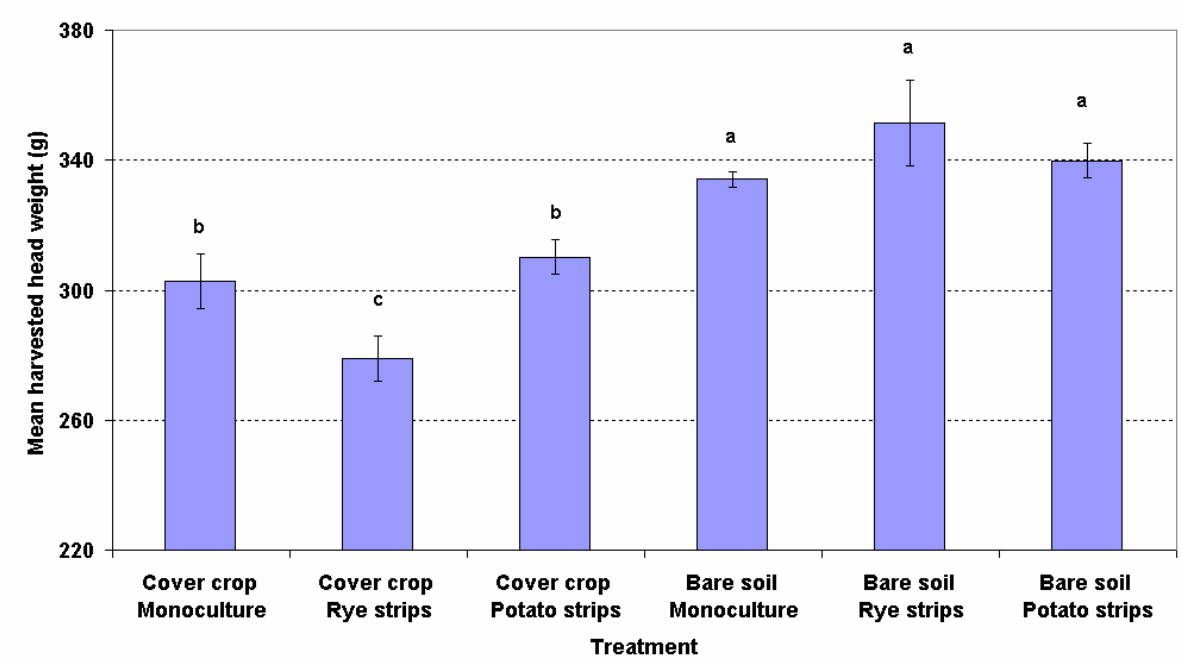


Table 5.15. The effect of treatment (six cropping systems) and planned comparisons of the harvested head weight per plant in 05/06. Significant results are shown in bold type.

Analysis	*df*	*F*	*P*
Treatment	5	13.92	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	56.58	**<0.0001**
Strip v. Monoculture	1	0.08	0.7863
Bare soil strip v. Bare soil monoculture	1	1.70	0.2070

When the broccoli harvested in 05/06 was assessed for quality the branching angle score (Figure 5.15 and Table 5.16), the shape score (Figure 5.16 and Table 5.17) and the hollow stem score (Figure 5.17 and Table 5.18) across the treatments were not significantly different. However, in all three quality indices the pairwise contrasts of the cover crop and the bare soil treatments were significant, indicating that the cover cropping treatments had

slightly better branching angle, shape and hollow stem scores and were therefore of marginally better quality than the bare soil treatments.

Figure 5.15. Mean branching angle score (1-5) in 05/06 ± SE, where 1=worst branching angle (unmarketable) and 5=best branching angle (highly marketable).

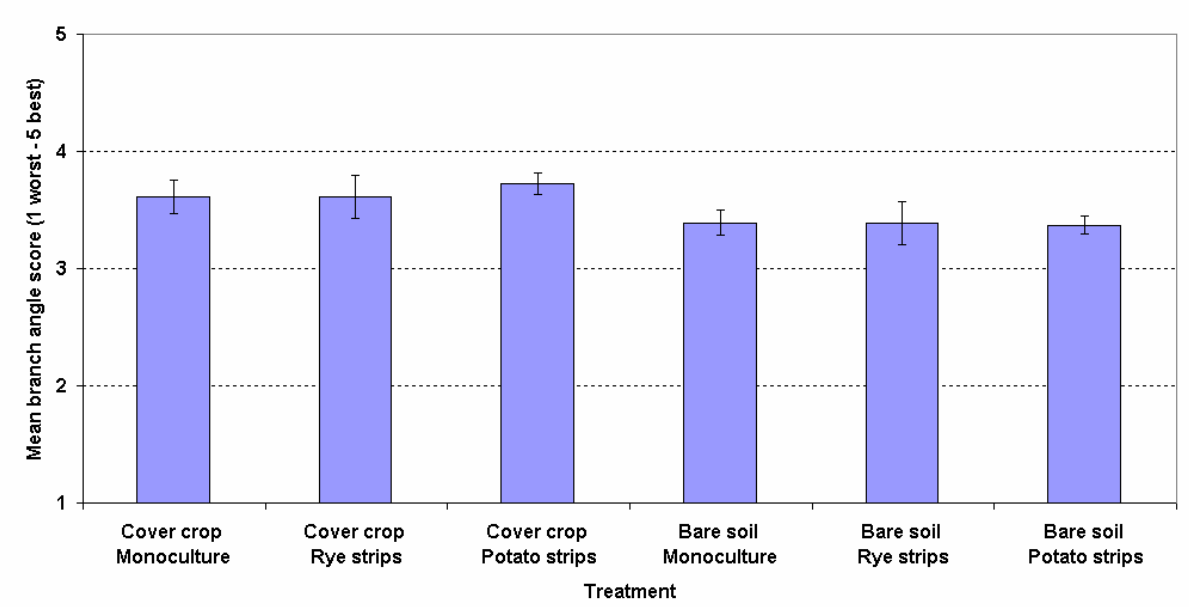


Table 5.16. The effect of treatment (six cropping systems) and planned comparisons of the branching angle score in 05/06. Significant results are shown in bold type.

Analysis	***df***	***F***	***P***
Treatment	5	1.13	0.3782
Contrasts			
Cover crop v. Bare soil	1	5.23	**0.0333**
Strip v. Monoculture	1	0.04	0.8496
Bare soil strip v. Bare soil monoculture	1	0.00	0.9582

Figure 5.16. Mean shape score (1-5) in 05/06 ± SE, where 1=worst shape (unmarketable) and 5=best shape (highly marketable).

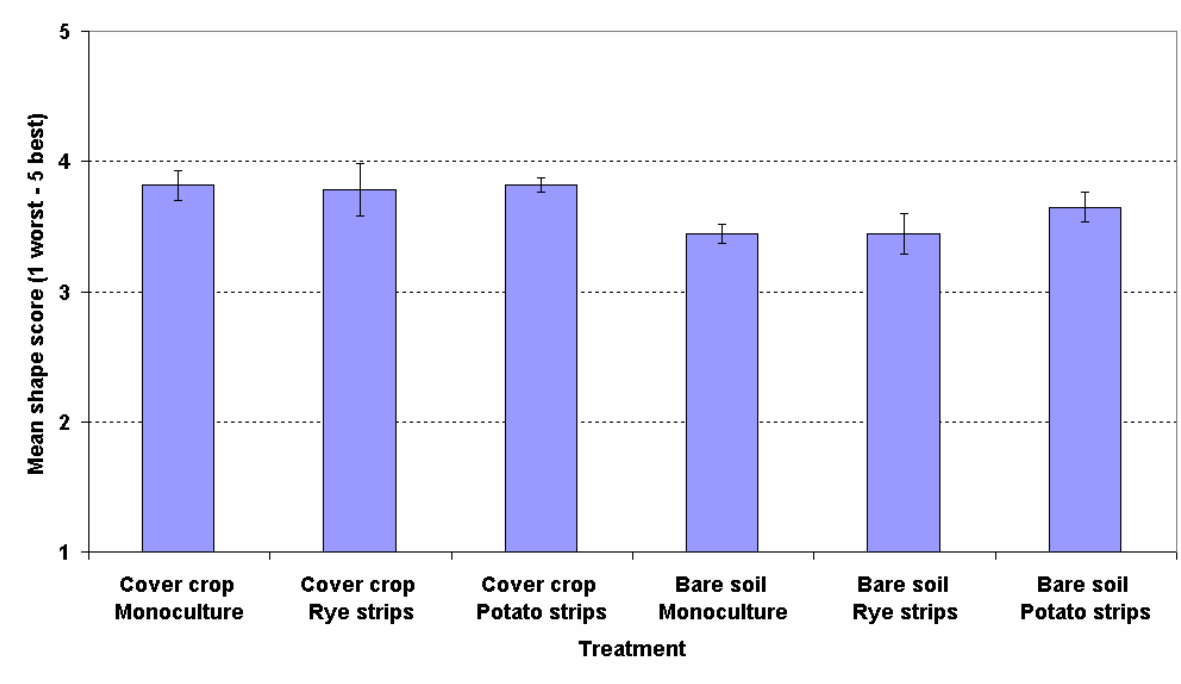


Table 5.17. The effect of treatment (six cropping systems) and planned comparisons of the shape score in 05/06. Significant results are shown in bold type.

Analysis	*df*	*F*	*P*
Treatment	5	1.52	0.2282
Contrasts			
Cover crop v. Bare soil	1	6.22	**0.0215**
Strip v. Monoculture	1	0.12	0.7335
Bare soil strip v. Bare soil monoculture	1	0.34	0.5680

Figure 5.17. Mean hollow stem score (1-4) in 05/06 ± SE, where 1=severe hollow stem and 4=no hollow stem.

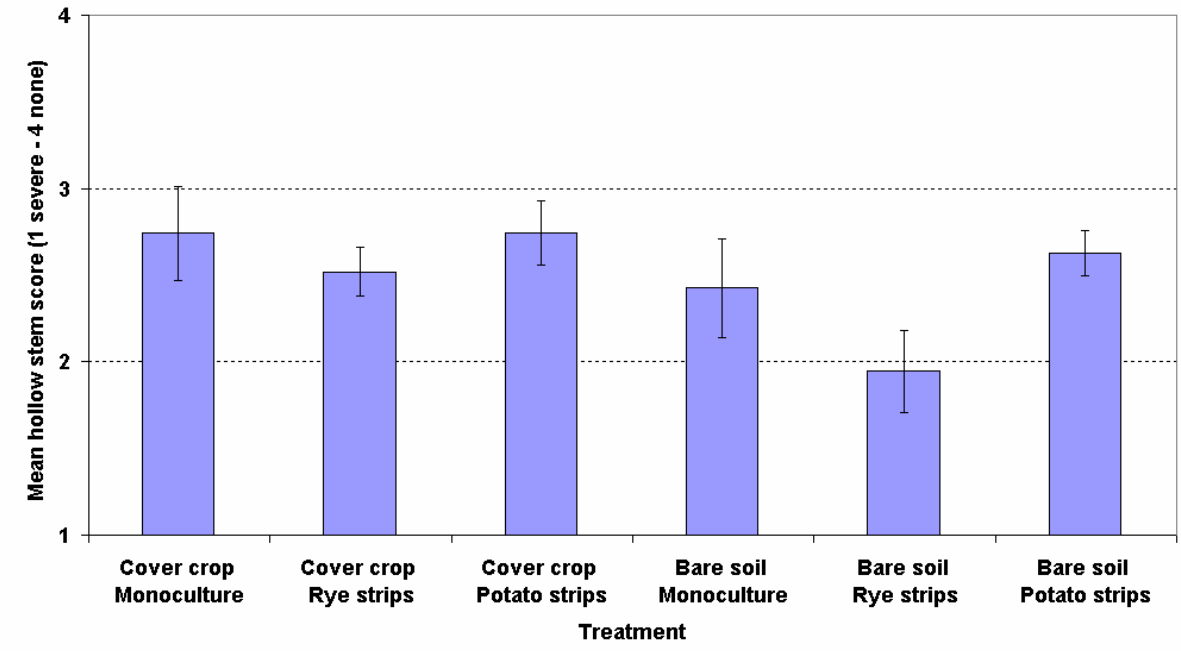


Table 5.18. The effect of treatment (six cropping systems) and planned comparisons of hollow stem score in 05/06. Significant results are shown in bold type.

Analysis	*df*	*F*	*P*
Treatment	5	2.49	0.0657
Contrasts			
Cover crop v. Bare soil	1	4.64	**0.0436**
Strip v. Monoculture	1	0.58	0.4551
Bare soil strip v. Bare soil monoculture	1	0.36	0.5562

5.3.6 Broccoli nutrient analysis 05/06

Of all the nutrients analysed, significant treatment differences were only found for potassium (K) with the cover cropping treatments having significantly higher K concentrations than the bare soil treatments (Figure 5.18 and Table 5.19). Similarly, the Bare soil/Monoculture had significantly higher K concentration than the Bare soil/Rye strips and the Bare soil/Potato strips treatments. Of all the pairwise contrasts for the remaining nutrients there was only one other significant result, with bare soil treatments having a slightly higher sulphur content than the cover crop treatments (F=10.75, df=1, P=0.0083).

Figure 5.18. Mean Potassium (K) content of nutrient sap tests in 05/06 ± SE. Treatments without a letter in common are significantly different (*P*=0.05).

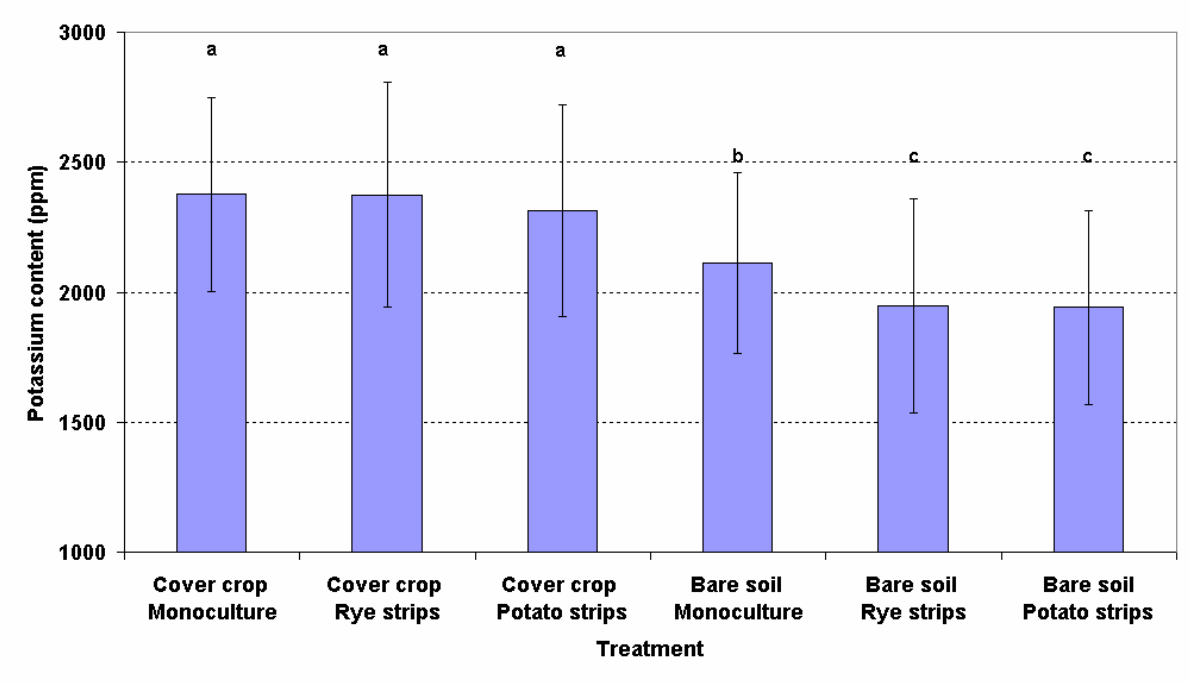


Table 5.19. The effect of treatment (six cropping systems) and planned comparisons of on the potassium content per plant in 05/06. Significant results are shown in bold type.

Analysis	*df*	*F*	*P*
Treatment	5	574.47	**<0.0001**
Contrasts			
Cover crop v. Bare soil	1	118.39	**<0.0001**
Strip v. Monoculture	1	8.39	**0.0159**
Bare soil strip v. Bare soil monoculture	1	11.80	**0.0064**

5.4 Discussion

5.4.1 Development, yield and quality

There were no significant yield differences between potatoes planted into a cover crop compared to potatoes planted into conventionally prepared (bare) soil in 04/05. This supports the findings of Wallace and Bellinder (1990) and Boyd *et al.* (2001) who found that reduced tillage potato systems using cover crops have no impact on yields when compared to conventional tillage. The potatoes in the strip cropping treatments of the 04/05 experiment were planted approximately one month before the broccoli was transplanted,

and the broccoli did not compete with the potatoes for light until approximately six weeks after planting. Hence, there was a period of approximately 10 weeks where there was less competition for light in the strip cropping treatments than in the potato monoculture treatments. However, this also did not result in significant differences in yield or quality.

In contrast to the potato results from the 04/05 experiment, results for broccoli in both the 04/05 and 05/06 experiments exhibited clear treatment differences in yield and quality. The rye cover crop resulted in less leaf and stem biomass and fewer, larger leaves in the cover crop treatments compared to the bare soil treatments. The cover cropping treatments also had lower yields of broccoli and harvesting was delayed by approximately one week. Offsetting this yield loss and harvest delay were increases in broccoli marketability/quality indices with improvements in branching angle and shape as well as reductions in the severity of hollow stem.

The lower leaf and stem biomass totals in the cover cropping treatments is one possible cause of the lower yield in these treatments, as less biomass accumulation will often result in lower yields. The leaf and stem dry weights decreased for all the treatments between 52 DAT and 59 DAT. The reduction in leaf dry matter was most likely the result of lower leaf senescence and detachment as the plant redirected carbohydrates to the inflorescence. Stem dry weights also declined between 52 and 59 DAT because the petioles of these lower leaves previously were pooled with the stems after the leaf material was stripped in the partitioning process.

A reduction in yield of broccoli planted into a desiccated barley (*Hordeum vulgare* L.) cover crop has been previously reported by Hoyt (1999) and attributed to lower soil temperatures expected under cover crop treatments as soil temperatures were positively correlated to yield. Cereal rye cover crops have also been reported to reduce soil temperatures (Teasdale and Mohler 1993). This reduction by cover crops of soil temperatures by several degrees, when compared to bare soil, was discussed in a review of literature by Lu *et al.* (2000) as a possible limitation to their use due to delaying harvest for several days or even longer.

Current broccoli development models rely on thermal time accumulation based on air temperatures and not soil temperature to determine time to head initiation (Fellows *et al.* 1997; Grevsen and Olesen 1999; Tan 1999; Tan *et al.* 2000). As the average air temperature at Forthside in January 06 and February 06 was approximately 16^{o}C, the data from Fellows *et al.* (1997) would indicate that a reduction in air temperature of 1^{o}C or more would result in more time to initiation, a delayed harvest and fewer leaves. However, as the cover crop was unlikely to significantly reduce air temperature these data cannot be used to directly determine the effects of lower soil temperatures.

The cover crop also resulted in less branching, fewer leaves and greater initial internode extension (longer stems). These responses are typical plant shade avoidance strategies (Smith 1982) as the broccoli plants were partially shaded by the rolled rye cover crop. Low light intensities brought on by shading of *Brassica napus* have been shown to cause a gibberellin mediated stem elongation response, which can indirectly reduce shoot dry weight (Potter *et al.* 1999). Despite a reduction in dry weight accumulation of approximately 11% in the leaves and 16% in the stems when compared to the bare soil treatments (at the last sample 59 DAT), the cover crop only reduced the average yield by approximately 7%. This indicates that broccoli grown in bare soil produces extra leaves and branches that do not directly contribute to yield. The prototype planter might have also affected the yield in the cover crop treatments due to reduced soil tilth and possible smearing of the planting slot. This is discussed in Chapter 6.

Broccoli that was grown immediately adjacent to potato plants had the greatest yield and also developed the quickest in all three experiments at Forthside from 2003 until 2006, however this was not significantly different from the bare soil monoculture treatment. This is despite a significant increase in the average head diameter compared to all other treatments between 52 DAT and 59 DAT in the 05/06 experiment. The comparison of the bare soil monoculture and bare soil potato strip treatments across the experimental years of 04/05 and 05/06 did not result in significant differences in average head weights (F=3.27,

df=1, *P*=0.0832) or significant differences in the number of days from transplanting to harvest (*F*=1.05, *df*=1, *P*=0.3158).

5.4.2 The effect of the cover crop on weeds

The bare soil treatments had to be weeded at least three times during the growing season whereas the cover crop treatments did not require weeding and yet still reached a reasonable yield (Masiunas 1998). This is important not only for the reduced weeding effort required in the cover crop treatments but also because there are currently no selective herbicides available in Australia for the control of weeds in broccoli and mechanical weeding in the cover crop is not a viable alternative due to the high levels of residue. While a direct comparison between treatments is impossible due to the absence of an unweeded control in a bare soil treatment, yields in an unweeded bare soil plot were likely to have been substantially reduced by weed competition for resources, as evidenced by the picture of a small unweeded area between two plots (Picture 5.6). The reduction in weed pressure by the cover crops, when compared to the bare soil treatments, was initially due to the early rapid growth of the rye, which acted to out-compete the weeds. Other factors limiting weed pressure were reduced soil disturbance at transplanting and less light penetration to the soil acting to reduce germination of weed seeds (Teasdale and Mohler 1993). Later on in the crop, the rolled rye cover crop formed a physical barrier that proved difficult for weeds to penetrate before exhausting seed energy reserves (Teasdale and Mohler 1993).

Picture 5.6. An unweeded area between two plots in 05/06 experiment

Further evidence for the effectiveness of the cover crop in controlling weeds came from the 2004/2005 experiment. In this trial there was a strip of wild radish (*Raphanus raphansitrum* L.) approximately 8m wide, which formed a thick carpet of seedlings that ran through the length of the trial (all three repetitions). This was possibly due to past chemical trial controls resulting in a huge seed bank in the soil. Wild radish is a very difficult weed to control and is strongly competitive in all situations (Hyde-Wyatt and Morris 1975). Picture 5.7 and Picture 5.8 illustrate the differences between the cover crop and the bare soil treatments. In Picture 5.7 the unweeded area between the different plots is covered in a thick carpet of wild radish while the cover crop treatment on the right has the weed largely under control.

Picture 5.7. Infestation of wild radish in the 04/05 experiment controlled by the rye cover crop on the right, with the interplot region marked with a black line. Note that the plot pictured in Picture 5.8 is in the background.

In Picture 5.8, even the cultivated areas between the two white markers have a significant infestation of wild radish. This infestation required chemical treatment before planting and significant manual weeding effort during the experiment, while the cover crop treatment (Picture 5.9) had low levels of wild radish infestation and did not require weeding. Therefore the cover crop had the ability to control this very invasive weed. However, to achieve this level of weed control a dense, uniformly distributed cover crop must be established prior to transplanting of the broccoli (Morse 1998).

Picture 5.8. Infestation of wild radish in a bare soil plot in the 04/05 experiment, with the interplot area marked with a black line.

Picture 5.9. Control of wild radish by the unweeded cover crop at 48 DAP in the 04/05 experiment

5.4.3 Economic implications of the rye cover crop in broccoli cropping systems

Despite the positive effects of the cover crop treatments in reducing the levels of two significant insect pests of broccoli (*P. xylostella* and *B. brassicae*) and hence a potential to reduce control costs as well as a slight increase in quality of the harvested product, there was a distinct negative impact on yield. It is important to determine if the negative impact on yield is offset by the positive effects thus making the use of cover crops a economic

proposition for broccoli producers. Using the outcomes of this Chapter and Chapter 4 it is possible to make an economic comparison of a broccoli production system using a rye cover crop with that based on conventional cultivation. This comparison was conducted using an enterprise budget and gross margin analysis based on an industry standard produced by DPIW (2005) (Table 5.20). This standard has a number of assumptions and is designed to be representative of what a competent operator, using industry standard practices, might achieve on a model farm experiencing satisfactory seasonal conditions (DPIW 2005). Some modification of these assumptions was needed to accommodate the specifics of the two contrasting systems and these are marked with a superscript letter (a to d). Yields estimates were derived from the treatment averages from the 05/06 experiment so that harvest quality could also be taken into account by removing unmarketable broccoli from the calculated means (that is, branching angle and shape scores of 1 and 2 as per recommendations from Tan [1999]). Based on this approach, the average head weight for the conventional practice (Bare soil/Monoculture) was 0.301 kg and the cover crop (Cover crop/Monoculture) was 0.282 kg. These figures were then multiplied by the target density of 33,000 plants/ha. In both the cover crop and the bare soil treatments the removal of the previous crop would require some cultivation. Therefore this analysis assumes that the cover crop was directly sown into the previous crop after this cultivation process using minimum tillage, while the conventional system was left fallow (although it is becoming increasingly common for farmers to plant a “green manure” crop of short-term grass to increase organic matter in the cropping rotation and prevent erosion over the winter period). Other assumptions were that the cover crop adequately suppressed weeds thus eliminating the need for mechanical weeding and the cover crop reduced insect pressure so that only one spray of insecticide for Lepidopteran larvae was required to ensure that the harvested product met quality standards.

The enterprise budget and gross margin analysis indicates that even though the cover crop system reduced the total variable costs by $323/ha (or 6.7%), the lower yield in the cover crop treatment reduced the total gross margin by $151/ha (or 5.9%) when compared to conventional practice of a bare soil monoculture. Based solely on these figures the practice of using a cover crop would be less attractive than maintaining conventional practice.

However, the yield point at which the cover crop monoculture produced the same gross margin as the bare soil monoculture was 9.507 tonnes/ha or 0.435 tonnes/ha less than the bare soil monoculture. This would equate to a yield improvement in the cover crop treatment of 0.202 tonnes/ha or just 2.2%, which with more research into transplanter design (Chapter 6), tailoring fertiliser strategies for cover crops (not just using conventional rates) and perhaps selecting cultivars more suitable to lower soil temperatures, is believed to be achievable. Alternatively, a price premium of only 7% due to perceived (and actual) improvements in the innate quality of the product through the use of a more ecologically acceptable cropping method (Theunissen 1994), would have the same result as the 2.2% yield increase.

Table 5.20. Broccoli crop enterprise budget of the Bare Soil Monoculture and the Cover Crop Monoculture Treatment harvest means and is based on current cash crop budgets (DPIW 2005).

						Bare soil	Cover crop
ENTERPRISE OUTPUT							
Yield per plant (kg)**:**						0.301	0.282
Yield: 33000 plants/ha						9.943	9.306
Price: $744 /tonne [a]						7398	6924
Total Enterprise Output						**7398**	**6924**
VARIABLE COSTS							
Materials:							
Speedling transplants in trays		33,000/ha	@	$44/1000		1452	1452
Lime - bulk, spread	33%debit of	5t/ha	@	$38/tonne		63	63
Fertiliser							
14:16:11- band placed at transplanting		500kg/ha	@	$592/tonne		296	296
Urea - topdressed		250kg/ha	@	$575/tonne		144	144
Sodium molybdate		1kg/ha	@	$17/kg		17	17
Cartage		750kg/ha	@	$13.50/tonne		10	10
Cereal rye seed for the cover crop		100kg/ha	@	$0.30kg			30
Pest Control							
permethrin	5sprays	0.1litre/ha	@	$80/litre		40	8 [b]
pirimicarb	5sprays	0.5kg/ha	@	$58.40/kg		146	0 [b]
Cover crop desiccation							
Glyphosate	1spray	2litre/ha	@	$9.60/litre			19
Tractor and Plant:							
#Land Preparation*		8.1hr/ha	@	$12.51/hr		101	13 [c]
#Cover crop desiccation	1spray	0.6hr/ha	@	$6.74/hr			4
#Topdressing Urea		0.6hr/ha	@	$6.74/hr		4	4
#Post planting cultivation	3 runs	1hr/ha	@	$12.51/hr		38	0 [d]
#Pest control	5sprays	0.6hr/ha	@	$6.74/hr		20	4 [b]
#Harvesting - intermittent running		1.5tonne/hr	@	$6.74/hr		52	52
Repairs, Maintenance & Lubrication on operations						96	40
Contract Operations:							
Soil Analysis	5ha	1analysis	@	$30.00/field		6	6
Planting of Speedlings		33boxes	@	$20.00/box		660	660
Harvesting	164kg/box	70bins	@	$21.00/box		1470	1470
Irrigation:							
Running costs		225mm/ha	@	$23.52/25 mm		212	212
Total Variable Costs						**4827**	**4504**
GROSS MARGIN						**2571**	**2420**

*Land preparation is assumed to consist of 1 Agrow ploughing, 1 rotary hoeing and 1 Roterra cultivation.

#Fuel cost only.

[a] Price based on 2006 projections in (Anon 2005)

[b] Assuming one spray of permethrin only

[c] Cover crop drilling cost only

[d] Assuming no post transplanting cultivation required

Chapter 6 Practical aspects of increasing crop species diversity: crop management and mechanisation

A shift away from monocultures to strip or cover cropping would require some modification to the way crops are managed. Changes would need to be made to land preparation, planting, inter-row cultivation, spraying and harvesting activities. Some of these aspects had to be addressed in this project, partly to ensure plots were managed properly. This enabled examination of some of the practical issues farmers are likely to confront if they decide to adopt these changes to their systems. Two novel pieces of machinery were designed, built and trialled during the course of the project. These were a five-metre wide low drift chemical spray unit and a broccoli roller/transplanter. This chapter details the development and testing of these two pieces of equipment and the associated rationale behind their development.

6.1 Development of a low drift spray unit

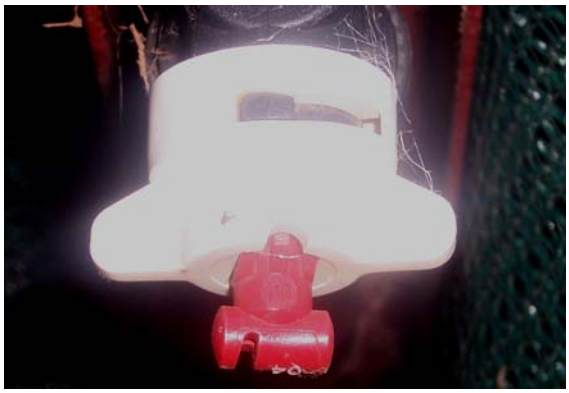
For the "Preliminary investigations" of 2003/2004 detailed in Chapter 3, each crop was planted in 5m wide strips. Due to the size of the experimental area, chemical applications with a small, knapsack type sprayer were impractical, which meant that the chemical applications had to be from a tractor-based boom spray. Most spraying equipment used in vegetable production systems in Tasmania are based on at least 12m boom widths and would not fit a 5m wide system. It would have been possible to use one side of a 12m boom spray on each strip, however this would have resulting in driving on the edge of each strip and the zone of interaction between crops, which was of significant research interest. A further problem was the potential for herbicides to "drift" into the neighbouring non-target crops, again reducing production or possibly killing the neighbouring crops. Therefore it was essential that a low drift, 5m spray rig be built in order to simplify management. This design could potentially be applied to any strip width to facilitate management of a commercialised strip cropping system.

Advice was obtained from a local spraying contractor Richard Murell from Beechworth Spraying Pty Ltd (Ulverstone, Tasmania). Mr Murell recommended that the low drift spray

jets from Turbo Teejet® (Spraying Systems Co) be used (Picture 6.1.a). These particular jets produce relatively large droplets when compared to fan jets, which when combined with high water rates of 400L/ha and lower pressure, would significantly reduce spray drift.

A 400L spray unit (Hardi A/S, Taastrup, Denmark), seven Turbo Teejets® and spray tubing were attached to a 6m boom so that the water fan created by the jets was projected slightly forward and across the direction of motion (Picture 6.1.b). When the sprayer was calibrated to use 400L/ha, there was adequate coverage and jet overlap for the 5m width. However, the two outermost jets (one from each side) over sprayed the 5m by approximately 300mm.

Picture 6.1. (a). Side view of a Turbo Teejet® (left). (b). Assembling the sprayer (right).



This over-spray was controlled with an end guard constructed from a 7mm thick rubber sheet with dimensions of 1m x 0.75m (Picture 6.2.a). The rubber was pop riveted onto a 1m piece of 25mm angle iron, which was welded to a 150mm length of 60mm square tubing. This tubing slid snugly over the spray boom and was fixed into position with two bolts (Picture 6.2.b). As Picture 6.2.a illustrates, the square tubing was attached to the guard in an offset position so that 400mm of the guard was in the direction of travel and 600mm was effectively behind the jets. This was designed to minimise the spray drift that would follow a tractor mounted sprayer. After initial trials, the edges of the rubber sheet were rounded to prevent snagging on the soil and plant material. To keep the rubber guard stiff and therefore straight, the end guard was also strengthened 100mm from the bottom edge by attaching a 25mm x 1m piece of flat bar (as indicated with a line of pop rivets from Picture 6.2.a).

Picture 6.2. (a). Sprayer end guard in profile with pop rivets indicated by the arrow (left). (b). The end guard attachment (right).

These design changes meant that the sideways spray drift was contained. There was some chemical runoff from the outer jet over-spray that hit the end guard, but this dripped out of harms way between the plant rows and did not damage any crop plants.

Picture 6.3. The end guard between two crops.

Further testing indicated upward spray drift was not completely contained when the sprayer was in operation. This was adequately contained by a sheet of nylon shade cloth stretched over the top of the spray boom and left slightly hanging behind the sprayer (Picture 6.4.a and Picture 6.4.b).

Picture 6.4. (a). Sprayer rear view (left). (b). The sprayer front view (right).

Once developed, the sprayer was used successfully used for all subsequent trial work in 03/04 and did not result in any adverse chemical damage to non-target neighbouring crops, provided that the crop rows were correctly spaced.

6.2 Development of the roller/transplanter

Currently, there are no no-till transplanters or specialised cover crop rollers commercially available in Australia. The lack of reliable no-till transplanters, resulting in inconsistent stand establishment, has been discussed as a major limiting factor to the adoption of no-till systems for transplanted crops (Morse 1998). Furthermore, to the best of the author's knowledge, there are no machines available that perform both tasks simultaneously. The main rationale behind building the roller/transplanter was to demonstrate to farmers and agronomists that broccoli could be mechanically transplanted into a cover crop and was therefore a feasible alternative to current practices.

The development of the roller/transplanter began with the planting of the cover crop in the 2004/2005 trial. The first task was to desiccate and roll the cover crop to form a thick bed of stem and leaf (Picture 6.5) (as discussed in Chapter 4).

Picture 6.5. Cover crop in the 04/05 experiment prior to desiccation and rolling.

The first attempt at rolling the cover crop was made with a conventional heavy roller with two trailing discs aligned to form slots for the transplants to be set into (Picture 6.6.a) It was immediately obvious that this roller was not suitable as the cover crop was not flattened and sprang back into place. As time was limited due to the cover crop being desiccated and the plantlets were on order, a manual solution had to be quickly developed. As a temporary fix, the cover crop was manually flattened with a hand operated crimping/flattening tool (Picture 6.6.b). This consisted of a 1.65m length of 40mm angle iron with a sharpened edge attached to a handle, which was manually pressed with a foot using body weight at approximately 200mm spacings, in much the same manner as spade is used. This proved to be effective, which indicated that the rye cover crop could be crimped and flattened with the downward pressure of body weight alone.

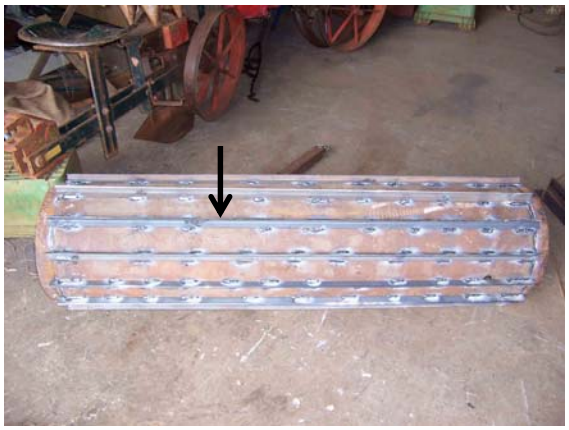
Picture 6.6. (a). The heavy roller with two trailing discs (left). (b). A demonstration of the angle iron flattener (right).

Existing transplanters are designed to operate in soil cultivated into a fine tilth and were unable to handle the large above ground biomass of the flattened and crimped cover crop. Therefore, establishment of the broccoli crop required hand transplanting into pre-fertilised 800mm rows (Picture 6.7.a and Picture 6.7.b).

Picture 6.7. (a). Pre-drilling fertiliser into a flattened cover crop (left). (b). Hand planting broccoli plants (right).

For the experiments in 2005/2006, which included an intensive trial at Forthside and a semi-commercial trial on a nearby farm at Gawler, a roller transplanter was manufactured. The basis of the roller was a 450mm diameter, 1.8m long sealed cylinder. Welded to this cylinder were 13 “crimpers” made from of 1.65m long bars of 5mm thick, 25mm angle iron positioned at intervals of approximately 80mm (Picture 6.8.a). The roller was then attached to a tractor mounted three-point linkage tool bar (Picture 6.8.b). The roller was offset by 200mm to give a slight slicing action as it rolled and crimped the cover crop. Testing of the roller indicated that it was effective in rolling the rye cover crop and able to create a consistent residue mat.

Picture 6.8. (a). Roller construction with the drum and angle iron "crimpers" indicated by the arrow (left). (b). Attaching the roller to the tractor tool bar (right).




The next phase of the development process involved attaching a fertiliser box to the tool bar. Having the roller offset meant that it was not practical for the fertiliser box to be driven from the roller. Therefore a ground driven wheel was attached to drive the gears of the fertiliser box (Picture 6.9.a). A horizontal piece of square tubing was also mounted on the tool bar to attach two cup transplanter units (Picture 6.9.b).

Picture 6.9. (a). The roller with the fertiliser box attached indicated by the arrow (left). (b). A cup planter unit indicated by the arrow (right).


The cup transplanters had no facility to drill fertiliser underneath the transplants. Therefore, a set of double disc openers were made from two 450mm diameter straight edge discs and attached to the cup planter (Picture 6.10.a). The double discs were touching at their leading

edge and 50mm apart at the trailing edge. This had the purpose of opening a slot for fertiliser to be deposited closely followed by the "boot" of the cup planter (to the left of the double disc and slightly in front of the press wheels in Picture 6.10.a), facilitating transplanting of broccoli at the appropriate depth. The initial field tests indicated that the rye residues could build up on the boot of the cup planter. To counter this, a trash guard was welded to the double disc attachment to guide the flow of the rye residues around the boot preventing a build up of trash (Picture 6.10.b)

Picture 6.10. (a). The double disc openers (indicated by the arrow) attached to the cup planter (left). (b). The trash guard (indicated by the arrow) attached to the double disc unit (right).

Further testing of the prototype planter (Picture 6.11) and planting of the semi-commercial trial (Picture 6.12) revealed that the double disc opening apparatus by itself was not sufficient to handle the high levels of residue in the cover crop treatments. This led to a build-up of trash on the double discs, which had to regularly removed and also necessitated the manual resetting of transplants. Both of these problems dramatically slowed down planting. A subsurface tiller as described by Morse (1998) was investigated as a possible solution but this also led to an unacceptable level of trash build-up.

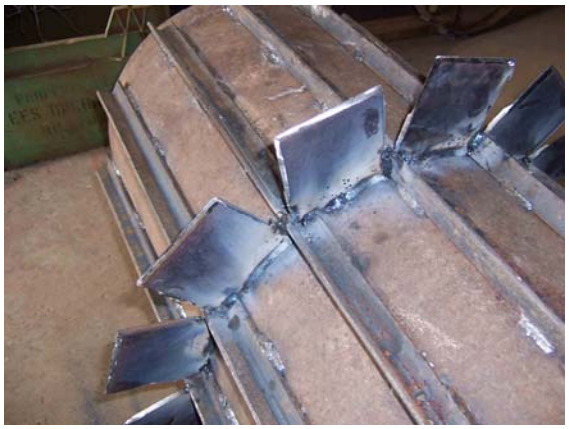
Picture 6.11. The prototype roller/transplanter ready for testing

Picture 6.12. The prototype roller/transplanter being tested in the semi-commercial trial in 05/06.

It appeared that a slot needed to be created for the double discs to open up. As there was not enough space for a disc between the planter and the roller, the slot maker was attached directly to the roller. This also meant that the roller could no longer be offset and had to be square to the direction of travel, which testing revealed did not hinder the rolling process.

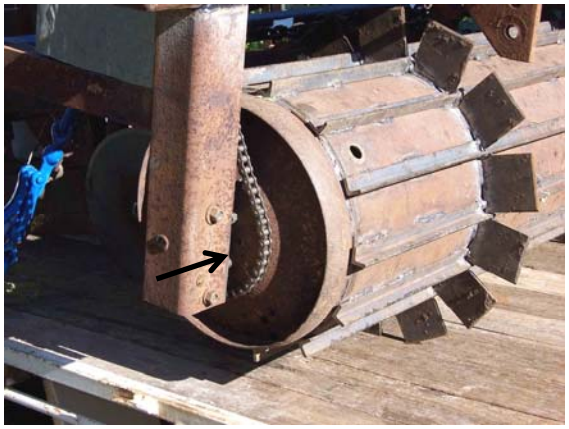
The slot maker itself consisted of 100mm square pieces of 5mm flat bar that were welded in line with the double discs and transplanting boot, in between the crimpers on the roller (Picture 6.13.a and Picture 6.13.b). These were then sharpened. Testing in a dry pasture paddock showed that the slot makers were immediately buried and very effective at creating the initial slot for the double discs to open up, despite this slot not being continuous due to the gaps between the slot makers.

Picture 6.13. (a). The second prototype roller with slot maker (left). (b). A close up of the slot makers (right).

The square realignment of the roller meant the fertiliser box could now be driven by the roller instead of an attached wheel (Picture 6.14.b) further simplifying the second prototype.

Picture 6.14. (a). The second prototype ready for testing (left). (b). The fertiliser box drive system attached to the roller (indicated by the arrow) (right).

It was at this stage that the development process ended because the final trial had to be planted. While the end result was acceptable (Picture 6.15) it was necessary to manually check each transplant to ensure uniformity between bare soil (conventional) and cover crop treatments.

Picture 6.15. The end result of the second prototype roller/transplanter, a rolled cover crop and transplanted broccoli (Cover crop/Rye strips Treatment).

6.2.1 Potential improvement to the roller/transplanter

To improve planting efficiency a number of further design modifications need to be considered including:

1. The addition of scrapers to remove soil that could build up on the slot makers attached to the roller.
2. Heavier wheels for the cup planter set on a greater angle to the ground could assist with pressing soil around the transplants and increasing soil contact.
3. The addition and modification of a subsurface tiller as described by Morse (1998) to fracture the soil and improve stand establishment.
4. The addition of a fluted type disc coulter, which can improve soil flow back into the slot formed, hence improving soil contact (Murray *et al.* 2006) with the transplant.

The last two points are important because the ferrosol (krasnozem) soil type on which the research was conducted typically has a high clay content. Soil with a high clay content is prone to smearing at the base and walls of the planting slot, which in extreme cases prevents the plants roots from spreading outside the slot (Murray *et al.* 2006). Therefore, any modification to the planter/roller that increased soil tilth in the slot created for the transplants or soil flow back into the slot, has the potential to increase yields of the broccoli when compared to the bare soil treatments.

6.3 Conclusion

This chapter demonstrates that it is possible to design, manufacture and successfully test mechanical solutions to meet the needs of novel cropping systems. Therefore, the absence of appropriate machinery should not be seen as a major barrier to the research and adoption of alternative cropping practices (Vandermeer 1989).

Chapter 7 General Discussion

The initial vision of this thesis was to investigate options for reducing the level of chemical inputs in vegetable cropping systems, while maintaining efficiency and productivity. This chapter discusses the major implications of this research and the relative sustainability of the cover cropping system developed compared to current conventional practices. Then future research directions and possible applications to other cropping systems are highlighted.

7.1 Pest control implications of this research

The research conducted in this study has shown that it is possible to manage some insect pests and weeds using a rye cover crop. Lewis *et al.* (1997) suggested that instead of focusing on the development of new synthetic chemicals or promoting the use of more benign or even "natural" chemicals like those extracted from *Bacillus thuringensis*, research should work towards designing farming practices that work with nature in order to prevent the elevation of an organism to pest status. The reduction in the prevalence of an important insect pest like *P. xylostella*, and to a lesser extent *B. brassicae*, by the rye cover crop, indicates that such a directional shift in agricultural research is plausible and that an increase in plant species diversity can form part of an effective insect pest control strategy. Conceptually, the cover crop acts like a broad-spectrum insecticide reducing, but not necessarily eliminating pests (Finch and Collier 2003). However, unlike broad-spectrum insecticides the overall reduction in numbers of *P. xylostella* eggs and larvae and *B. brassicae* colonies also has the potential to increase the effectiveness of "soft" insecticides (such as *Bt* formulations) and beneficial insects. These findings are of special significance for the control of *P. xylostella*, as this insect has shown the ability to become resistant to every insecticide applied in the field (Sarfraz *et al.* 2006). Furthermore, in Australia where *P. xylostella* is typically the only major pest of Brassica crops (Baker and Kovaliski 1999), there is no evidence of regional genetic differentiation of *P. xylostella* populations due to frequent migration (Endersby *et al.* 2006), which means that insecticide resistance that develops in one area has the potential to spread around the country. Therefore any non-chemical control measures for *P. xylostella* could have important consequences for the

long-term production of vegetable Brassicas by potentially reducing insecticide use and/or delaying the development of insecticide resistance.

7.2 Financial implications of this research

In addition to the potential to control insect pests and reduce insecticide use, this study has shown that the rye cover crop can sufficiently suppress weeds to an extent that no additional weed control strategies were required. However, this study has identified a number of costs associated with cover crops. The rye cover crop changed the morphology, growth and development of the broccoli plants to the extent that yield was reduced and harvest time delayed by about a week. The negative impact of a yield reduction would be offset to some degree by small gains observed in the quality indices of the broccoli crop and cost reductions associated with reduced cultivation for weed control and fewer insecticide applications. A financial analysis of the cost/benefit tradeoffs showed that farmers would be marginally worse off adopting the revised cover crop based system, with a 7% reduction in the gross margin obtained. However, a sensitivity analysis indicated that minor improvements in yield (~2%) or a small price premium (~7%) would account for the shortfall compared to the current system. The delay in harvest time is unlikely to be of major concern as this is a fast growing crop that is ready for harvest in 9 to 10 weeks. One extra week of growth is unlikely to hinder future cropping options and this can be factored into planting schedules to ensure timeliness of supply to markets.

7.3 Environmental implications of this research

The costs and benefits of the rye cover crop are not purely financial as there are some positive environmental outcomes that could be derived from using the revised system. Conventional broccoli crops are typically planted into soil of a fine tilth, which requires approximately three tractor operations using various implements. The subsequent crop would then be weeded approximately three times using a tractor mounted inter-row cultivar and sprayed up to five times with insecticides (DPIW 2005). The total number of insecticide applications for the number of crops grown over a year could be as high as 35 (Baker and Kovaliski 1999). It is envisaged that the cover crop would be planted directly into the previous crop after some minor cultivation with an implement like a rotary hoe.

The cover crop would grow for two-three months and then be killed with one application of glyphosate. Glyphosate is the best choice of herbicide to kill the cover crop as it will also kill broadleaf weeds and has no residual effects on the subsequent crop. The cover crop would then be rolled and broccoli transplanted into the residues. The crop would not be weeded and would require no insecticide or possibly only one application. Using this comparison, the cover crop would use less cultivation than a conventional system, less (or no) insecticide but would require one application of glyphosate. Therefore, when considering the overall environmental benefits of the cover crop, the relative toxicity of these inputs must also be considered. Using data from the Material Safety and Data Sheets for all insecticides registered for use on broccoli in Australia and three herbicides (Table 7.1), the glyphosate formulation Roundup® (Monsanto, St. Louis, Missouri) is relatively less toxic than all the insecticides except *Bt* formulations and perhaps spinosyns, especially if using the "frog friendly" formulation Roundup Bioactive® (Monsanto, St. Louis, Missouri). Furthermore, both the 04/05 and the 05/06 experiments only required a single spray of glyphosate to kill the cover crop, while insecticides are typically used more frequently. If management of the cover crop with glyphosate was inadequate or poorly timed so that the cover crop was not completely controlled before transplanting, a selective grass herbicide such as fluazifop-p butyl could be used to kill the cover crop and not harm broccoli. While fluazifop-p butyl is less toxic than most of the insecticides listed below, it is a less desirable alternative than glyphosate and should only be used as a last resort. There is also the potential to kill the cover crop by mechanical means, thus eliminating the need for herbicides and reducing costs (Ashford and Reeves 2003), further enhancing the overall sustainability of the system compared to conventional practices.

Table 7.1. Toxicity of insecticides registered for broccoli in Australia (APVMA [2006] and associated Material Safety Data Sheets)

Insecticide Chemical subgroups	Name/s	Toxicity to Mammals	Toxicity to Fish	Toxicity to Birds	Notes
Carbamates	Methomyl Pirimidicarb Thiodicarb	Toxic	Toxic	Non-toxic to Toxic	Repeated exposure can have a cumulative poisoning effect

Insecticide Chemical subgroups	Name/s	Toxicity to Mammals	Toxicity to Fish	Toxicity to Birds	Notes
Organo-phosphates	Chlorpyrifos Diazinon Dimethoate Methamidophos Phorate Prothiofos Trichlorfon	Toxic	Toxic	Toxic	All are toxic and some are very toxic. Can cause kidney and liver damage
Cylodiene	Endosulfan	Toxic	Very toxic	Toxic	Kidneys, liver and other organs can be significantly affected
Phenylpyrazoles	Fipronil	Mildly toxic	Toxic	Can be toxic	Can cause severe irritation and damage to the eye
Pyrethroids/ Pyrethrins	Alpha-cypermethrin Beta-cyfluthrin Deltamethrin Permethrin Tau fluvalinate	Toxic	Extremely toxic	Toxic	Can cause skin sensitisation
Neonicotinoids	Imidacloprid	Non-toxic	Toxic	Toxic	Rapidly immobilised by the soil
Spinosyns	Spinosad	Non-toxic	Slightly to moderately toxic	Non-toxic	Relatively benign product
Piridine azomethine	Pymetrozine	Non-toxic	Non-toxic	Non-toxic	Antifeedant only active on xylem feeders
Bacillus thuringensis	*Bacillus thuringiensis*	Non-toxic	Non-toxic	Non-toxic	Toxic only to caterpillars of certain Lepidopterous insects
Chlorfenapyr	Chlorfenapyr	Toxic	Toxic	Toxic	May adversely affect mites predators and other beneficials
Avermectin	Emamectin benzoate	Low toxicity	Toxic	Not stated	Mild irritant

Insecticide Chemical subgroups	Name/s	Toxicity to Mammals	Toxicity to Fish	Toxicity to Birds	Notes
Indoxacarb	Indoxacarb	Toxic	Toxic	Toxic	May cause eye and skin irritation and haemolytic anaemia
Herbicides					
Glyphosate	Roundup®	Non-toxic	Harmful (surfactant)	Non-toxic	LD_{50}s all greater than 5000mg/kg
Glyphosate	Roundup Bioactive®	Non-Toxic	Non toxic	Non-toxic	Much less toxic to aquatic life and amphibians with this formulation
Aryloxyphenoxy-propionate	Fluazifop-p Butyl	Non-toxic	Toxic	Low-toxicity	Repeated or prolonged exposure can cause liver and kidney disorders and embryo/foetotoxic effects.

When these all these factors are combined with other known benefits of ground cover, including reducing soil erosion (Roberts *et al.* 1999) and pesticide runoff into water ways (Fawcett *et al.* 1994), it could be argued that transplanting broccoli into cover crops is a more sustainable proposition than conventional production methods which rely on cultivation to control weeds and insecticides to control insects. If these benefits were effectively marketed, the cover cropping system might achieve the price premiums required to achieve financial parity with conventional production systems.

7.4 Future research directions

The success of cover cropping compared to strip cropping indicates that future research efforts should focus on increasing plant species diversity in the vertical plane (above and below) rather than the horizontal plane (side by side). Agronomic aspects of this further research in the vertical plane should initially focus on:

- improving the design of the roller/transplanter to improve plant establishment and yield through better transplant/soil contact and reduced soil smearing;
- identifying solutions to soil temperature constraints on growth, including the selection of crop genotypes better suited to the system and altering planting dates;
- reducing the cost of production of the cover cropping system by including a nitrogen fixing plant like a clover or vetch in the cover cropping to reduce the level of nitrogenous fertiliser required; and
- determining minimum cover crop biomass requirements to improve planting operations through residue reductions while also reducing seed costs and potential crop competition.

The results from this study indicate that the effect of the cover crop on *P. xylostella* and *B. brassicae* were due to interference with colonisation processes. However, it cannot be determined if this interference caused female *P. xylostella* moths and alate *B. brassicae* to emigrate from the area; have difficultly finding plants; or in the case of *P. xylostella*, lay fewer eggs. Therefore further research should investigate the actual mechanism of this colonisation interference. One possible research method could be the use of video surveillance equipment to closely monitor *P. xylostella* and *B. brassicae* behaviour in a similar fashion to experiments of Cleary *et al.* (2006) with *Helicoverpa armigera* (Lepidoptera: Noctuidae).

The cover cropping strategy may be effective in other cropping systems with significant insect pest issues, however generalisations regarding the impact of the rye cover crop on the behaviour of insects are problematic due to the different behaviours of various pests, as the results from *P. rapae* indicate. Therefore, the nature of the cover crop and its management ought to be tailored to the specifics of the commercial crop in question and should only be considered where it is able to significantly reduce populations of economically significant insects. Reducing colonisation should be the aim of this diversification strategy to keep infestations under the economic thresholds.

The study has also shown that a cover crop could be effective on small insects that are relatively weak fliers with poorly directed flight, such as other species of aphids and possibly thrips (Thysanoptera), as alate *B. brassicae* appeared to have difficulty successfully locating host plants. There are already indications that rye residues negatively affect thrips in cotton and peanuts (Olson *et al.* 2006). There are also indications that the same mechanisms that inhibited *P. xylostella* host location might also operate on other major Lepidopteran pests as wheat stubble can negatively impact *Helicoverpa* spp. in cotton (Cleary *et al.* 2006). This could quite possibly be due to the adult *Helicoverpa* sp., like *P. xylostella*, being mainly active at night (Zalucki *et al.* 1986). Therefore adult insect temporal (day/night) behaviour is worth further consideration as a possible component of the mechanisms of the interference with colonisation processes in the cover crop.

Chapter 8 Summary of research findings

The major findings from this research are:

- The rye cover crop significantly reduced the populations of *P. xylostella* and *B. brassicae* presumably by interfering with host location/colonisation processes.
- The rye cover crop had no effect on *P. rapae* due to the insect's highly developed host location processes and random egg distribution behaviour.
- Strip cropping had no significant benefits and there were no additive effects as strip cropping and cover cropping combined were no better than cover cropping alone.
- The cover crop significantly reduced plant biomass accumulation and yield, but marginally improved quality.
- The economic analysis of the findings from this research revealed that the cover crop reduced the gross margin of broccoli production by approximately 6% when compared to conventional bare soil monocultures. However, this difference could be eliminated by a 2.2% improvement in yield or a 7% price premium for using fewer chemicals.
- It is possible to design, build and successfully test mechanical solutions to problems associated with the cropping systems trialled, including accurate chemical applications in strip crops and transplanting broccoli into a high biomass cover crop.
- Any interaction between plants in a strip cropping system are likely to occur in the narrow zone where the plants are immediately adjacent to each other.
- Fungal diseases of the vegetable crops studied were too virulent and ubiquitous to be controlled with strip cropping alone.
- Onions are poor competitors and not a suitable component of the strip cropping system trialled.

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Appendices

Appendix A Example ANOVA models from Chapter 3

Table A1. ANOVA model and planned comparisons of the average weight (kg) of onion samples with various neighbouring plant configurations in 03/04. Significant results are shown in bold type.

Model effects	***df***	**Type III Sum of Squares**	***F***	***P***
Neighbour	4	68.1884420	0.91	0.4668
Plot	6	913.8437163	8.13	**<0.0001**
Error	43	805.690586		
Contrasts				
Broccoli edges vs. Onion monoculture	1	24.98006990	1.33	0.2546
Potato edges vs. Onion monoculture	1	45.75715611	2.44	0.1255
Plot edges vs. Onion monoculture	1	53.59460069	2.86	0.0980
Strip middle rows vs. Onion monoculture	1	32.53441198	1.74	0.1946
Strip cropping vs. Monoculture	1	36.42516012	1.94	0.1704

Table A2. ANOVA model and planned comparisons of the average weight (kg) of potato samples with various neighbouring plant configurations in 03/04. Significant results are shown in bold type.

Model effects	***df***	**Type III Sum of Squares**	***F***	***P***
Neighbour	7	50.9973388	0.78	0.6096
Plot	6	544.2923458	9.65	**<0.0001**
Error	94	883.502800		
Contrasts				
Both broccoli edge rows vs. Potato monoculture	1	2.20379609	0.23	0.6294
Outer broccoli edge rows vs. Potato monoculture	1	0.11627586	0.01	0.9117
Both onion edge rows vs. Potato monoculture	1	0.00025463	0.00	0.9959
Outer onion edge rows vs. Potato monoculture	1	0.04846243	0.01	0.9429
Both plot edge rows vs. Potato monoculture	1	1.68055556	0.18	0.6734
Outer plot edge rows vs. Potato monoculture	1	0.00576190	0.00	0.9803
Middle strip rows vs. Potato monoculture	1	6.02257977	0.64	0.4255
Strip Cropping vs. Monoculture	1	1.23816671	0.13	0.7175

Appendix B Example ANOVA models from Chapter 4

Table B1. ANOVA model and planned comparisons of the effect of treatments (four cropping systems) on the abundance of *P. xylostella* larvae 12 days after transplanting in 04/05

Model effects	***df***	**Sum of Squares**	***F***	***P***
Treatment	3	0.0197222	1.07	0.3694
Block	2	0.01449074	1.18	0.4288
Error	6	0.03680556		
Contrasts				
Cover crop v. Bare soil	1	0.01814815	2.96	0.1362
Strip v. Monoculture	1	0.00148148	0.24	0.6406

Table B2. ANOVA model and planned comparisons of the effect of treatments (six cropping systems) on the abundance of *P. xylostella* adult moths female moths 36 days after transplanting in 05/06.

Model effects	***df***	**Sum of Squares**	***F***	***P***
Treatment	5	5.00000000	0.80	0.5627
Block	5	12.66666667	2.03	0.1184
Row	5	8.33333333	1.33	0.2907
Error	20	25.00000000		
Contrasts				
Cover crop v. Bare soil	1	0.44444444	0.36	0.5577
Strip v. Monoculture	1	0.12500000	0.10	0.7551
Bare soil strip v. Bare soil monoculture	1	0.02777778	0.02	0.8830

Appendix C Example ANOVA models from Chapter 5

Table C1. ANOVA model and planned comparisons of the effect of treatments (four cropping systems) on total potato yield in 04/05

Model effects	***df***	**Sum of Squares**	***F***	***P***
Treatment	3	169644166.7	0.10	0.9561
Block	2	514940416.7	0.46	0.6503
Error	6	3338179583		
Contrasts				
Cover crop v. Bare soil	1	9187500.0	0.02	0.9019
Strip v. Monoculture	1	157081666.7	0.28	0.6143

Table C2. ANOVA model and planned comparisons of the effect of treatments (six cropping systems) on number of leaves per plant 14 days after transplanting in 05/06. Significant results are shown in bold type.

Model effects	***df***	**Sum of Squares**	***F***	***P***
Treatment	5	0.07818204	2.19	0.0955
Block	5	0.06931169	1.95	0.1315
Row	5	0.09203712	2.58	0.0586
Error	20	0.14253754		
Contrasts				
Cover crop v. Bare soil	1	0.03540919	4.97	**0.0374**
Strip v. Monoculture	1	0.00098058	0.14	0.7146
Bare soil strip v. Bare soil monoculture	1	0.01093225	1.53	0.2299