

Lincoln University Digital Thesis

Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- you will use the copy only for the purposes of research or private study
- you will recognise the author's right to be identified as the author of the thesis and due acknowledgement will be made to the author where appropriate
- you will obtain the author's permission before publishing any material from the thesis.

The effect of landscape- and local- scale non-crop vegetation on arthropod pests and predators in vineyards

A thesis submitted in partial fulfilment of the
requirements for the Degree of
Doctor of Philosophy
at
Lincoln University
by
Mariska S. R. Anderson

Lincoln University
2012

"if you knew what you were doing it wouldn't be called research"

Albert Einstein

“Hofstadter's Law: It always takes longer than you expect,
even when you take into account Hofstadter's Law.”

Douglas Hofstadter

Abstract of thesis submitted in partial fulfilment of the requirements
for the
Degree of Doctor of Philosophy

**The effect of landscape- and local-scale non-
crop vegetation on arthropod pests and
predators in vineyards**

by

Mariska S.R. Anderson

Abstract

Experiments were conducted to assess any influence of the landscape and local ('field' scale) non-crop vegetation on conservation biological control (CBC) via predation of insect pest eggs in vineyards.

In the 19th Century, world industry including agriculture was based on coal. In the 20th Century, oil was the main energy source while many believe that this century, a bio-economy will become the norm. This not only applies to energy sources but to new and more sustainable ways of growing the world's food and beverages. For example, the United Nations has produced a number of strategic reports on this topic, including the work of de Schutter (2010)

http://www.unep.org/publications/ebooks/foresightreport/Portals/24175/pdfs/Foresight_Report-21_Issues_for_the_21st_Century.pdf. In this, it was strongly suggested that agro-ecology is the only way of feeding the human population of nine billion, which is expected in a few decades.

De Schutter suggested that in developing countries, yields can double in one decade if this system were to be adopted. In 'developed' countries, the same conclusion applied

although the absence of the appropriate government policies is currently restraining this approach.

Vineyards worldwide are aspiring to a more sustainable approach to viticulture and a current worldwide surplus is accelerating moves in that direction, including the conversion of some vineyards to organic viticulture. A key driver for these changes is the need to reduce variable costs in vineyards (pesticide, herbicide, fungicide, fuel and labour). However, wine growers are largely bereft of appropriate and topical advice to help them in this. Although some specific pest-management protocols do exist (e.g., the deployment of flowering buckwheat; *F. esculentum* between vines to provide nectar for beneficial insects), little attention has been paid to whether or not these local, within-vineyard practices are the most appropriate way of enhancing ecosystem services (ES) such as insect biological control. This thesis, therefore, addresses a wider, landscape scale and investigates whether landscape features outside the vineyard itself influence the numbers and phenology of invertebrate pests, and predators and their predation efficacy. To investigate this, geographic information systems (GIS) were used to examine the relationship between the landscape of the Waipara Valley, New Zealand, in relation to the above variables. Invertebrate trapping was carried out but to address more accurately the dynamics of the system, surrogate prey comprising eggs of the light brown apple moth, *E. postvittana* and the tomato/corn ear/boll worm, *H. zea* were used in 25 vineyards. Egg disappearance rates were assessed by 'before and after' counts, usually after 24 hours and by infra-red illuminated digital, movement-sensitive video. It was concluded that, in fact, there were few landscape effects on these measurements. Subsequent within-vineyard manipulation of the between-row flora, using herbicides, showed that such simple management techniques involving leaving some 'weeds' between the vine rows had a substantial effect on pest predation rate. This latter result means that viticulturalists who aspire to a non-monoculture vineyard have a readily available service-providing unit (SPU) at their disposal at low cost. This work also strongly supports the aspirations of the United Nations, among other international bodies, for farming to move towards being part of a bio-economy.

Acknowledgements

I would like to give a massive all-encompassing thank you to my supervisor Steve Wratten for his dedication to my attainment of this doctorate and the support, confidence-building, motivation and enthusiasm in all aspects of this work. Steve, I am also very grateful for the lightning speed turnaround of constructive feedback and your open door policy - even when I've just shown up in your office to talk about wine.

Another massive thank you to my associate supervisor James Ross – although officially titled as such rather late, your calm advice and help whenever I needed it was always appreciated. I would also like to thank Hannah Buckley, without whom I would never have learned 'R', which to my surprise I very much enjoyed.

I would like to thank all of my colleagues at Lincoln University for their assistance and support. Mark Gillespie, Jean Tompkins, Kay Sakata and Sofia Orre-Gordon, thank you for being such patient and accommodating office mates, and good mates to have gone through this process in general! Special thanks to Mark for keeping me amused during our days in Waipara. Also thank you to Marco Jacometti, Mattias Jonsson, Dean O'Connell, Ken Hughey, Sue Worner, Sandy Hamilton, Anna-Marie Barnes, Shona Sam, Corrine Staley, Nathan Curtis, Marlene Leggett, Ben Hancock and all of the other great people I've met on the road to fortune and glory. Thank you for the coffee breaks, the smiles and that wry understanding of similar obstacles faced.

Similarly, I'd like to wholeheartedly thank my industry mentor, Jean-luc Dufour, without whom I would never have been able to do any of this – Jean-luc, your calm and careful help was amazing. Help was available wherever I needed it, but crucially, from Anne Barrington, Les Wright and Richard Townsend - the technical reality of this work would not have been possible without your specific skills, thank you so much.

I was allowed almost free rein on 25 vineyards and I am very grateful to all the people I met in the Waipara valley winegrowing region, thank you very much for letting me introduce pests into your vineyards, and trusting me to take them back out again!

An enormous heartfelt thank you to my mum, Jan, without whose support, love and belief in me I would never have made it this far. I dedicate this thesis to you, mum – thank you, I love you.

Jeff, The Bampy, I don't even know where to begin to thank you. You are and have been my best friend and inspiration, supporter, motivator, encourager, shoulder to cry on, success co-celebrator and I love you insurmountably! You've been there for me,

and shared so much and I am just floored by your kindness and generosity. No one writing a thesis has ever been so well taken care of. Thank you also to Jeff's family for their care, encouragement and support, in particular Jeff's Dad, Ron, without whom I would not have learned so much about the 'sustainable harvest' of whitetail deer (a.k.a. hunting). It makes me very sad to acknowledge that Ron passed away before he could see this finished product, but I'm reassured he'd be proud.

I would also like to acknowledge the financial support of the Technology for Industry Fellowship (NZVY0701) without which none of this research would have been possible.

Thank you all very much.

Contents	Page
Abstract	3
Acknowledgements.....	5
Figures.....	10
Tables.....	12
Chapter 1:	
Introduction.....	13
1.1. General introduction.....	13
1.2. Biological control	15
1.3. Non-crop vegetation and natural enemies.....	17
1.3.1 Landscape scale non-crop vegetation and natural enemies.....	17
1.3.2 HMS in local non-crop vegetation and natural enemies.....	19
1.4 The study system.....	22
1.4.1 Greening Waipara and the study site.....	22
1.4.2 Waipara grapevines and their pests and their natural enemies.....	24
1.4.2.1 The ‘model’ sentinel bait species.....	29
1.4.3 The New Zealand Wine industry.....	29
1.5 Aims.....	30
Chapter 2:	
Pest abundance in Waipara Valley in relation to surrounding habitats.....	32
2.1 Abstract.....	32
2.2 Introduction.....	33
2.3 Methods.....	35
2.3.1 Immigration into vineyard by <i>C. zealandica</i>	35
2.3.2 Counts and collection of <i>E. postvittana</i> larvae on grape bunches.....	38
2.3.3 Statistical analysis.....	39
2.4 Results.....	41

2.5 Discussion.....	47
2.5.1 Prospects for biological control using local and landscape ‘barriers’ against <i>C. zealandica</i> and <i>E. postvittana</i>	48

Chapter 3:

The effects of the surrounding landscape on *Epiphyas postvittana* and *Helicoverpa zea* ‘sentinel’ egg baits.....49

3.1 Abstract.....	49
3.2 Introduction.....	50
3.3 Methods.....	51
3.3.1 Statistical analysis.....	53
3.4 Results.....	54
3.5 Discussion.....	56
3.5.1 Overview.....	56
3.5.2 The ability of the surrounding landscape to supply biological control...56	
3.5.3 The predator response.....	57
3.5.4 Conclusions.....	58

Chapter 4:

The effects of vineyard habitat management on *Epiphyas postvittana* and *Helicoverpa zea* ‘sentinel’ egg baits.....59

4.1 Abstract.....	59
4.2 Introduction.....	60
4.3 Methods.....	61
4.3.1 Statistical analysis.....	62
4.4 Results.....	63
4.5 Discussion.....	68
4.5.1 Overview.....	68
4.5.2 Local habitat management to enhance biological control: influence on predation rate.....	68
4.5.3 The predator response.....	71
4.5.4 Conclusions.....	71

Chapter 5:



Video analysis of predation rate of two lepidopteran ‘sentinel’ prey in relation to inter-row vegetation.....	73
5.1 Abstract.....	73
5.2 Introduction.....	74
5.3 Methods.....	77
5.3.2 Statistical analysis.....	79
5.4 Results.....	80
5.5 Discussion.....	85
5.5.1 Overview.....	85
5.5.2 Lack of predatory arthropod diversity.....	85
5.5.3 Location and treatment effects on predators and predation rate.....	86
5.5.4 Differences between predators’ behaviour.....	87
5.5.5 Conclusion.....	88

Chapter 6:

Discussion.....	90
6.1 Introduction.....	90
6.2 The ability of non-crop vegetation to provide CBC at the landscape and local scale.....	91
6.3 Effects of non-crop vegetation on arthropods in vineyards at the landscape and local scale.....	94
6.4 Future research.....	95
6.5 Conclusions.....	97
References.....	100

Figures	Page
Figure 1.1 Example of ‘stacked’ ES which may be provided by habitat management plantings (from Fiedler <i>et al.</i> (2008)).....	14
Figure 1.4.1.1 ‘Tourist’ map of Waipara. Adapted from ‘Waipara Valley Map’ from www.waiparawine.co.nz	23
Figure 2.3.1: Vineyards in Waipara Valley used in this study.....	36
Figure 2.3.2. Directional interception trap in vine row, Mud House vineyard, Waipara Valley.....	37
Figure 2.3.2.1 Diagram showing 5 rows in a vine block, arrows indicating direction, from which LBAM larval sampling took place.....	38
Figure 2.4.1 Principal components analysis plot showing the relationship the 2 principal components have with vineyards in the Waipara valley.....	42
Figure 2.4.2 Scree plot derived from the PCA, comparing components’ relative influence on vineyards.....	43
Figure 2.4.3 The mean number (\pm SE) of <i>C. zealandica</i> adults caught in traps in two locations (‘open’= within the vine block and ‘shelterbelt’=adjacent to a vine block), in two summer seasons (November-January 08/09 and 09/10) in 25 vineyards.....	46
Figure 2.4.4 The mean number (\pm SE) of <i>C. zealandica</i> adults caught in traps in vineyard blocks with different inter-row vegetation in 25 vineyards over two summer seasons (Nov-Jan 08/09 and 09/10 together). MS = mixed sward, Ryegrass = ryegrass, Ryemown = mown ryegrass. Traps were set in either an ‘open’ vineyard block, or near a ‘shelterbelt’.....	46
Figure 3.3.1 Sentinel egg bait experiment layout – either on the ground, pegged directly beneath the vine rows, or in the canopy, stapled to undersides of grapevine leaves.....	52
Figure 3.4.1 Pie chart comparison showing the percentage of landscape each variable (component) occupies. Variables shown in the lighter grey are non-correlated and were used in the analysis.....	54
Figure 4.4.1: Comparison of the proportion of <i>H. zea</i> eggs predated in the vine canopy at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at four time periods.....	65
Figure 4.4.2: Comparison of the proportion of <i>H. zea</i> eggs predated on the ground at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at three time periods.....	65

Figure 4.4.3: Comparison of the percentage of <i>E. postvittana</i> eggs predated on the ground at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at three time periods.....	66
Figure 4.4.4: Comparison of the percentage of <i>E. postvittana</i> eggs predated in the vine canopy at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at four time periods.....	66
Figure 4.4.5 Comparison of the percentage of <i>E. postvittana</i> eggs predated on the ground at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at three time periods, with three different between-vine ground covers; ryegrass (left to grow), ryegrass mown (mown as per normal management) and MS (mixed sward).....	67
Figure 5.3.1 IR camera placement and experiment design (example) in a vine block at Mud House Wines, Waipara.....	79
Figure 5.4.1 Comparison of the percentage of time/camera night spent on baits by two predator species in herbicide treated areas vs. control areas, in two locations: the edge of the vineyard block, and centre of the vineyard block (see Figure 5.3.1).....	81
Figure 5.4.2 Average number of visits by predators each night in control areas.....	82
Figure 5.4.3 Average number of visits by predators per night in herbicide areas.....	83
Figure 5.4.4 Average number of visits by predators to baits at the edge of the vine block, regardless of treatment.....	83
Figure 5.4.5 Average number of visits by predators to baits in the centre of the vine block, regardless of treatment.....	84

Tables	Page
Table 2.3.3.1 Different categories of landscape areas around the Waipara valley and how they were defined.....	40
Table 2.4.1 Principal components analysis variance matrix showing the proportion of variance in the data accounted for by each principal component (2 d.p.).....	43
Table 2.4.2 Principal components analysis loadings matrix showing the correlations (2 d.p) between each landscape variable and the first three principal components. Stronger correlations (>0.4, positive or negative) are shown in bold.....	44
Table 2.4.3 Correlations analysis showing standardized and uncorrelated landscape variables.....	45
Table 2.4.4 Generalised linear mixed model (GLMM) analysis for adults of <i>C. zealandica</i> in vine blocks in 25 vineyards in Waipara valley. Location = the effect of position in the vine block (next to shelterbelt or centre).....	45
Table 3.4.3 Generalised linear mixed model (GLMM) analysis for <i>H. zea</i> and <i>E. postvittana</i> , comparing landscape effects of non-vine vegetation on predation in vine blocks in 25 vineyards in Waipara valley. Local effects (<i>in italics</i>) are included as they are part of the landscape, but discussed in Chapter 4.....	55
Table 4.4.1 Generalised linear mixed model (GLMM) analysis for <i>H. zea</i> and <i>E. postvittana</i> , comparing local effects of non-vine vegetation on predation in vine blocks in 25 vineyards in Waipara valley. Landscape effects (<i>in italics</i>) are included as they likely impact the local effects, but are discussed in Chapter 3.....	64
Table 5.3.1 Randomisation of herbicide, control, edge and centre assignments to each camera.  =herbicide,  = control, 'E' = edge, 'Ce' = centre. Each night, the cameras were in a different randomly assigned treatment area.....	78
Table 5.4.1 A repeated measures REML for length of time of predator presence on baits. Treatment = the effect of herbicide areas, Location = the effect of position (edge or centre), Species = H or E.....	81
Table 5.4.2 Total time (h:min:s) spent on sentinel egg baits by each predator species in each treatment (see Table 4.4.1).....	82
Table 5.4.3 Generalised linear mixed model (GLMM) analysis for <i>H. zea</i> and <i>E. postvittana</i> predation rate of ground baits in a vine block at Mud House winery in Waipara valley. Location = the effect of position in the vine block (edge or centre).....	84

Chapter 1: Introduction

1.1 General introduction

The world human population is predicted to grow to 9 billion by year 2050 (U.S Census Bureau 2006). Unless food production can be increased, a population crash is likely. Modern intensive agriculture has seen losses in biodiversity through habitat fragmentation and disturbance, straining the provision of ecosystem services (ES) such as biological control, pollination and the provision of clean air and water etc. (Daily *et al.* 1997). Ecosystem services are necessary for long-term sustainable and profitable production, their global value being estimated at US\$33x10¹²/year with biological control (BC) worth US\$417x10⁹/year (Costanza *et al.* 1997) and BC services to agriculture from insects alone worth \$57 billion/year worldwide.

Modern agriculture aims to maximise yield and profitability (Benton *et al.* 2003). It contributes significantly to the NZ economy; for example, agricultural exports amounted to NZ\$31.5 billion for 2011 (Ministry for the Agriculture and Forestry 2011). This may not be sustainable; however, because the frequent, intense disturbance linked with high-intensity agricultural practices results in an environment low in the required physical and biological resources needed by the natural enemies of crop pests (Powell 1986, Letourneau 1998, Landis *et al.* 2000, Zehnder *et al.* 2007), resulting in a decline in biological control and other ecosystem services (Landis *et al.* 2000). Provision of key components of biodiversity through ‘ecological engineering’ can at least partly restore this ecosystem service and create more sustainable agriculture (Gurr *et al.* 2004). One of several approaches in utilising ecosystem services to help achieve sustainable management in agriculture is the use of conservation biological control (Landis *et al.* 2000).

The focus of this thesis is on conservation biological control (CBC) of pests in a vineyard, influenced by landscape and local scale non-crop vegetation. The aim of CBC is to enhance natural enemy population size and modify their behaviour and effectiveness by manipulating the environment to increase survival, fecundity, fitness (the contribution of a genotype to the next generation (Campbell *et al.* 1999)), and

longevity (Landis *et al.* 2000). Biological control and other ecosystem services (e.g. aesthetics, biodiversity conservation, waste water treatment and pollination) can work in synergy, therefore improvement of CBC may lead to improvement of weed suppression, for example. Fiedler *et al.* (2008) consider habitat management strategies that benefit multiple ES goals. They refer to ES as being ‘stacked’ (Fig. 1.1).

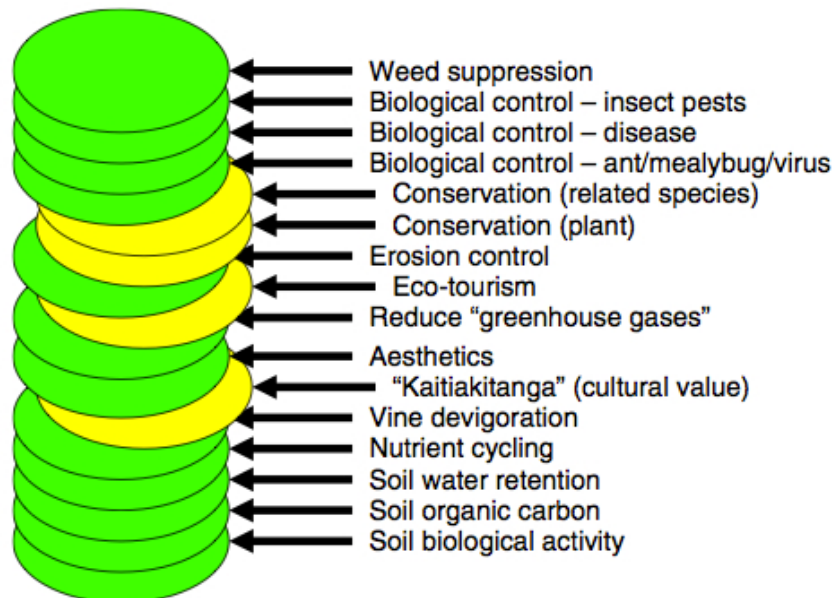


Figure 1.1 Example of ‘stacked’ ES that may be provided by habitat management plantings (from Fiedler *et al.* (2008)).

This thesis will evaluate the influence of non-crop vegetation on pest abundance, and predation of pests in a vineyard both at the landscape scale, and at the scale of the local, individual vineyard.

This introduction will explain the major concepts of CBC with an emphasis on non-crop vegetation, and its influence on the arthropods in this vineyard ecosystem.

1.2 Biological control

Biological control is the enhancement of the natural suppression of insect populations by parasitoids, predators or pathogens (De Bach and Rosen 1991). There are three approaches to biological control: classical, augmentative and conservation.

In classical biological control new, usually exotic, natural enemies are introduced into an area in the hope that they will establish and provide control of the target pest (van Driesche and Bellows 1996).

Augmentative biological control involves the release of one or more natural enemy species during a stage of crop growth when the natural enemies are not able to provide control such as newly planted crop areas where the natural enemy has not yet arrived or the population is too low. The control can be inundative, where large numbers of individuals released provide the control of the target pest, or inoculative. Inoculative control is used where the offspring of the individuals released are expected to colonise the area and provide control (van Driesche and Bellows 1996).

Conservation biological control (CBC) uses different strategies to manipulate the environment, aiming to enhance natural enemy survival, population size, fitness, fecundity, longevity and efficacy. These strategies may include providing nectar and pollen food sources, or alternative prey or hosts, providing shelter sites or maintaining existing refuges and minimising mortality from pesticide use (Gurr *et al.* 2000).

Historically, classical biological control has had some striking successes, but only 5-15% of introductions have been effective against targeted arthropod pests (Greathead and Greathead 1992, Gurr and Wratten 2000). This low success rate may be due to scarcity of other resources the natural enemy requires (Gurr and Wratten 1999).

Providing the natural enemy with supportive resources such as overwintering sites and alternative sources of food has been shown to improve pest parasitism and predation. The parasitoid *Copidosoma koehleri* Blanchard (Hymenoptera: Encyrtidae) was introduced in Australia to provide control of the potato moth (*Phthorimaea operculella* Zeller (Lepidoptera: Gelechiidae)), a key pest of potatoes in many countries (Gurr and Wratten 1999). While *C. koehleri* did become

established, the potato moth continues to be an important pest in New South Wales, Australia. However, it has been shown that increased parasitism of *P. operculella* can be achieved by providing food to *C. koehlerii*, improving the longevity of the insect, both in the lab and in the field (Baggen and Gurr 1998). Baggen *et al.* 1999 found that longevity of caged *C. koehlerii* could also be improved by supplementing the potato crop with flowering phacelia (*Phacelia tanacetifolia* Benth (Hydrophyllaceae)) and nasturtium (*Tropaeolum majus* L. (Tropaeolaceae)). This also works in different agricultural environments, such as the vineyard. A study by Begum *et al.* (2006) has shown that flowering alyssum in vineyards improves fecundity in the parasitoid *Trichogramma carverae* Carver (Hymenoptera: Tricogrammatidae, a natural enemy of light brown apple moth (LBAM) leafroller caterpillar (*Epiphyas postvittana* (Walker) Lepidoptera: Tortricidae). In CBC, habitat management strategies, such as planting flowering plants for natural enemies, are used to produce alternative patterns of abundance and biomass across more than one trophic level. Supplying natural enemies with resources they need to be most efficacious may result in lower abundance of the herbivorous pest (mid level consumers) and therefore a higher abundance of crop plants (first level producers) (Carpenter and Kitchell 1993).

Habitat management in agroecosystems can be used to provide natural enemies with otherwise limited resources (Landis *et al.* 2000, Gurr *et al.* 2004a, Jonsson *et al.* 2008), and is a way of implementing CBC that is accessible for growers to use. One example where this approach has been successful is in the control of the light-brown apple moth *E. postvittana* (LBAM), an invasive leafroller in New Zealand. In some cases, leafroller densities can be reduced to below the economic threshold when buckwheat (*Fagopyrum esculentum* Moench. (Polygonaceae)) in flower is available (Cullen *et al.* 2010). Provision of buckwheat has now been adopted as a measure to control leafrollers in vineyards in all major wine regions of New Zealand.

In CBC, habitat manipulations techniques, such as adding flowering buckwheat to vineyards, are used to produce an enhanced ‘top-down‘ effect to increase the natural enemy population (Gurr *et al.* 2000). However, habitat manipulation can produce effects that are consistent with the ‘resource concentration’ hypothesis in addition to the ‘natural enemies’ hypothesis. According to the ‘resource concentration’

hypothesis herbivores are more abundant in simple systems like monocultures, than in more complex systems (Root 1973). The reduction in herbivore numbers is caused by mechanisms such as ‘dilution’ of the contrast between a concentrated crop and the soil. This produces an attenuation of the visual and chemical cues normally indicative of a definite food source for the herbivore, resulting in reduced colonisation rates and increased emigration rates. These factors contribute to a reduction in damage to the crop (Gurr *et al.* 2000). As the herbivore population in the ‘resource concentration’ hypothesis is determined by a lower trophic level the effects seen are ‘bottom-up’ effects. The ‘natural enemies’ hypothesis postulates that predators and parasitoids more numerous and/or effective in more diverse systems than in simple ones (Root 1973). As the herbivore population in the ‘natural enemies’ hypothesis is determined by a higher trophic level the effects seen are ‘top-down’ effects. These ‘top-down’ effects are exploited in CBC, to increase the impact of natural enemies by providing key resources and by minimizing pesticide-induced mortality (Gurr *et al.* 2000).

1.3 Non-crop vegetation and natural enemies

1.3.1 Landscape-scale non-crop vegetation and natural enemies

The composition of the surrounding landscape and the distribution and availability of resources for natural enemies within the crop, such as alternative prey and habitat, may determine the extent to which particular resource ‘subsidies’ may be needed. Thies and Tscharrntke (1999) found higher parasitism rates of rape pollen beetles near field edges than the centre of the field in simple agricultural landscapes; however, there was no difference in landscapes with higher non-crop diversity. Therefore, resource subsidies available in the surrounding landscape may influence the local habitat management and conservation of natural enemies in some environments. Landscape dynamics can affect predation by natural enemies (Gardiner *et al.* 2009), parasitism by natural enemies (Thies and Tscharrntke 1999), natural enemy density (Schmidt *et al.* 2005) and species diversity (Schmidt *et al.* 2008). While many habitat management studies have been conducted at the field scale, these studies suggest that the composition of the surrounding habitat at larger spatial scales may be an important influence on habitat management strategies (HMS).

Different non-crop habitats in the landscape may provide specific resources for different natural enemies. Meadows, water margins and forests can supply key resources to natural enemies (Kruess and Tscharrntke 1994, Corbett and Rosenheim 1996, Bianchi *et al.* 2008). Natural enemy species move about the landscape in response to the distribution of non-crop vegetation and habitat at varying spatial scales (Bianchi *et al.* 2006). For example, high abundances of ballooning spiders have consistently been found within and up to several kilometres from non-crop habitats (Schmidt and Tscharrntke 2005a). Schmidt *et al.* (2008) found high densities of ballooning spiders correlated with landscape composition six kilometres diameter around the crop. Other mobile species such as parasitoids have also been found to respond to the proportion of non-crop habitat but at a smaller range of half a kilometre to two kilometres (Thies *et al.* 2005). However, several studies have shown a correlation between parasitism rate and non-crop habitat is most significant at one kilometre diameter around the crop (Thies *et al.* 2003, Thies *et al.* 2005, Bianchi *et al.* 2008). There are exceptions to these patterns – for instance, parasitoid diversity and rate of parasitism are not necessarily associated with increasing landscape complexity (Menalled *et al.* 1999).

Many natural enemy species, particularly generalist predators, do not disperse at large spatial scales (Schmidt *et al.* 2005). However, they may still be affected by non-crop habitats at the landscape scale. Increased densities of predators have earlier been reported in structurally complex landscapes with abundant woody habitats compared with simple landscapes (Elliott *et al.* 1998, Elliott *et al.* 2002, Schmidt and Tscharrntke 2005, Schmidt *et al.* 2005). For example, complex landscapes (in this case, substantial areas of wooded habitats) increased predation of *Mamestra brassicae* L. (Lepidoptera: Noctuidae) caterpillars (Bianchi *et al.* 2005). Such reliable results are not always found; however, and landscape scales that enhance predators can be different for the same groups even in closely related regions (Schmidt *et al.* 2008).

Variability of vegetation in the landscape may also influence natural pest control at the field scale. The ability of generalist predators to move between different non-crop vegetation and crops may allow early season colonization of crops from adjacent non-crop overwintering habitats (Bianchi *et al.* 2006). Then, pest populations have less time to grow, and control of the pest is more likely to be successful (Landis and van

der Werf 1997). Non-crop vegetation also provides a valuable refuge from disturbance from agricultural practices, decreasing mortality and discouraging emigration (Landis *et al.* 2000).

Overall, agricultural landscapes with a high proportion of non-crop habitat may support more natural enemy species than simple, monocultural landscapes. However, there are exceptions, and requirements of the landscape by different natural enemies are expected to be varied. This is likely to have implications for habitat management strategies to improve biological control on agricultural land.

1.3.2 HMS in local non-crop vegetation and effects on natural enemies

Habitat manipulation, a form of conservation biological control (Gurr *et al.* 2000) used in agricultural and horticultural management plans, is used at a wide range of ecological levels. From the scale of the microhabitat (soil, individual plant and local plant community), to the field, field border and adjacent communities and the landscape scale in which fields are embedded (Gurr *et al.* 1996, Landis *et al.* 2000), habitat management strategies (HMS) can be implemented. The structure of both the crop and non-crop vegetation at the local scale may influence natural enemy abundance and activity through a variety of mechanisms (Jonsson *et al.* 2010). At the field level, this can include effects on predator mobility, availability of shelter and alternative food sources. Populations of natural enemies can be reduced by agricultural practices such as application of chemicals, harvesting, mowing etc., and their persistence may be limited if there are no locally available populations in nearby non-crop habitats that can reinvade crops after these disturbances (Kruess and Tschamtkke 1994, Nicholls *et al.* 2000).

Individual growers can effectively alter vegetation near cropland at the local level as providing vegetation adjacent to crops and/or cover crops can be implemented easily (Gurr *et al.* 2003). An increase in populations of spiders, coccinellids, staphylinids, parasitoids and lacewings has been observed at this level in a number of studies (Landis *et al.* 2000, Hossein *et al.* 2002, Scarratt 2005, Berndt and Wratten 2005).

Higher abundances of natural enemies can often be more effective in the control of pests and this increased pest control through predation or parasitism has been observed in response to local vegetation. Parasitism of grape leafhoppers (*Erythroneura elegantula* Osborn (Homoptera: Cicadellidae) and predation of *M. brassicae* were significantly higher when woody vegetation was nearby (Corbett and Rosenheim 1996). Light brown apple moth (*E. postvittana*) suffered higher rates of parasitism when floral subsidies were present (Scarratt 2005, Irvin *et al.* 2006) and there was significantly more predation of *E. postvittana* eggs where cover crops were employed in a vineyard (Danne *et al.* 2010).

In a review of habitat manipulation studies, Jonsson *et al.* (2010) found 14 out of 15 studies reported positive effects of habitat manipulation, such as non-crop vegetation, on natural enemy abundance or predation or parasitism rates. However, this positive response to non-crop habitat is not always found beneficial to all natural enemies (Rand and Tscharrntke 2007). Jonsson *et al.* (2010) report that a key predator *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae) of an aphid species fed on extrafloral nectaries on adjacent peach trees rather than on the pest.

The optimal outcome is where the pest population decreases and less damage is done to the crop; however, non-crop vegetation can unintentionally benefit the pest itself. In the Jonsson *et al.* (2010) review, four out of seven studies found pest densities decreased with habitat manipulation, yet in one study the pest population increased near planted flower strips. For this reason it is vital that the implications of any habitat management strategies employed are fully understood i.e., which predators and/or parasitoids are active, what non-crop vegetation effects there may be on them and the target pest/s. Few studies show any positive effects of local non-crop vegetation on reducing crop damage (Jonsson *et al.* 2010).

Non-crop vegetation can also provide shelter and habitat, creating an environment more protected from the disturbances created by conventional agricultural practice. Disturbance not only displaces or kills many natural enemies, particularly non-flying species, it can also affect natural enemy interactions with hosts and/or prey (Van Driesche and Bellows 1996). Sharley *et al.* (2008) investigated tillage effects on natural enemies in a vineyard and found it significantly decreased all invertebrates.

The sharp decline in invertebrate numbers Sharley *et al.* (2008) observed was considered likely due to mortality, either from mechanical damage or burying (Thorbeck and Bilde 2004). Beetle abundance in maize was also found to have declined after tillage (House 1989).

House and Del Rosario Alzgaray (1989) (from Sharley *et al.* 2008) observed a significant reduction in numbers of Formicidae whose population took three to four months to re-establish after tillage. The study by Sharley *et al.* (2008) observed reestablishment of earwig populations after one month. However, this may not always be the case for all invertebrates or all types of mechanical disturbance; Hossain *et al.* (2000) found that a large population of predatory arthropods survived mechanical harvesting. Abundance of predatory beetles was found to have increased after tillage in a vineyard (Sharley *et al.* 2008). Such a dramatic negative effect on one order of invertebrates compared to another emphasizes the importance of understanding each species in an agroecosystem (Jonsson *et al.* 2010).

Tillage disrupts the non-crop vegetation, which is likely to have detrimental flow-on effects to most natural enemies through loss of habitat and other benefits of non-crop vegetation, such as alternative hosts for parasitoids. Herbicide applications also result in bare ground with no benefits to most natural enemies (Sharley *et al.* 2008). However, this may not mean there are no beneficial predators around where herbicide has been used. Burnip *et al.* (2002) found higher numbers of earwigs in cardboard rolls on woody plants in herbicide treated plots in an orchard, compared with pea straw mulched plots. The reason is unknown, although one hypothesis is that the cardboard rolls were not preferred over the pea straw, just that in herbicide treated plots, they offered better shelter than any alternatives (Burnip *et al.* 2002).

Other disturbances, such as mowing and harvesting, do not remove all non-crop vegetation, and may not cause as much mortality (Hossain *et al.* 2000) but still affect natural enemies in negative ways. In a study of mowing frequency in a pear orchard, Horton *et al.* (2003) found significantly lower densities of predatory, parasitic and some phytophagous arthropods on ground cover that had been mown two to three times per month compared to mowing once a month. In some cases disturbance such as harvesting may be an opportunity for improved pest control. Hossain *et al.* (2002)

found both arthropod pests and natural enemies in greater abundance in unharvested lucerne (*Medicago sativa* L.) adjacent to ‘just’ harvested crops. While this immediate response also increased pest abundance, Hossain *et al.* (2002) consider this use of unharvested crops as refuges by natural enemies a positive response. Natural enemies are likely to aggregate and reproduce in order to take advantage of this short term ‘enhancement’ of pests (Hossain *et al.* 2002).

Non-crop vegetation management and disturbance through agronomic practices may have different effects on different invertebrates, pests or natural enemies. Unfortunately no one rule exists for growers interested in improving conservation biological control within their habitat management strategies.

1.4 The study system

1.4.1 ‘Greening Waipara’ and the study site

The Waipara valley is situated 65 kilometres from Christchurch city in Canterbury, New Zealand (Figure 1.4.1.1). While its history is in sheep farming, it is now best known as a winegrowing region; there are 1,500 hectares of vines planted throughout the valley (www.waiparawine.co.nz). The landscape of Waipara is dominated with vineyards and surrounding pasture, by small areas of native flora and other non-crop vegetation in the form of shelterbelts and individual properties’ own plantings, gardens and trees.

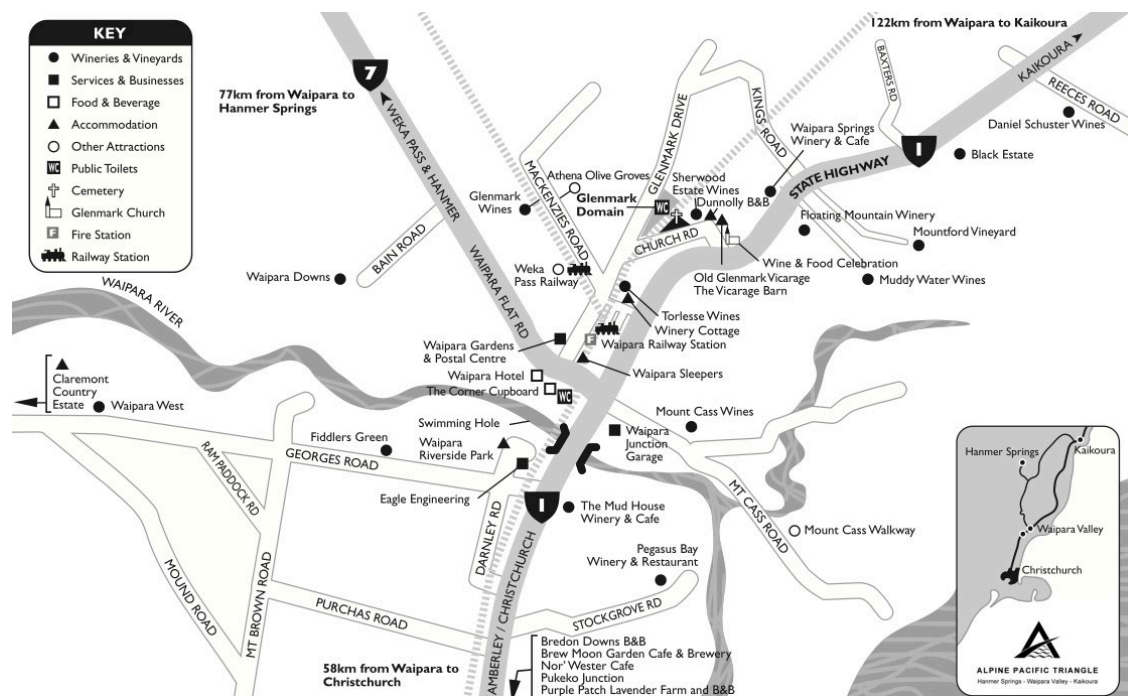


Figure 1.4.1.1 ‘Tourist’ map of Waipara. Adapted from ‘Waipara valley Map’ from www.waiparawine.co.nz.

The Waipara valley is also home to the ‘Greening Waipara’ project. This project began when studies showed that biological control of the light-brown apple moth (*E. postvittana*) can be improved if the non-native plant species buckwheat (*F. esculentum*), alyssum (*Lobularia maritima* L.) and phacelia (*P. tanacetifolia*) are drilled between the rows of vines (Scarratt 2005, Berndt *et al.* 2006, Irvin *et al.* 2006). This led to attempts to find native plants that can have a similar effect (Tompkins 2009) and a focus on how these can provide ecosystem services other than biological control and contribute to conservation (Fiedler *et al.* 2008). The aim is to conserve these remaining undisturbed habitats, and introduce native and non-native plant species that provide additional biodiversity, and improved ecosystem services (ES). ES such as biological control of pests, pollination, improved soil quality, conservation and eco-tourism add value to vineyards and can help reduce reliance on herbicides and pesticides. Winegrowers that joined the Greening Waipara programme have a shared goal and receive information about research into ES and how that can implement ES strategies in their vineyards.

1.4.2 Waipara grapevines and their pests and natural enemies

Most insect pests in New Zealand vineyards are polyphagous, they will feed on an array of agricultural crops and include thrips, mites, mealybugs and leafrollers (Bowie *et al.* 2002). Grass grub beetles are also becoming recognised as a pest in vineyards, as they feed voraciously on new grape leaf growth, reducing productivity of the vine for up to two years (Dufour *pers.comm.* 2008, Holding *pers.comm.* 2008).

Mealybugs and leafrollers are also significant pests in the New Zealand wine industry, transmitting leafroll virus (Jordan 1993) and causing damage, reducing vine productivity. However, this thesis will focus on the leafroller caterpillar and the grass grub beetle, and the predatory arthropods observed in Chapter 5 (Chapter 5: Video analysis of predation rate of two lepidopteran ‘sentinel’ prey in relation to inter-row vegetation). Leafroller caterpillars and grass grub beetles are both pests in Waipara that are often close to or exceeding their ‘economic threshold’, (5% incidence) whereupon chemical control may be used (Dufour *pers. comm.* 2008).

Leafroller caterpillar and parasitoid *Dolichogenidea tasmanica* Cameron (Hymenoptera: Braconidae)

There are six species of leafrollers (Lepidoptera: Tortricidae) considered important pests of grapes and other berry fruit crops in New Zealand (Harris 1994). Of these, *E. postvittana* is one of the most significant pests of grapes and other horticultural crops in the South Island of New Zealand (Scott 1984). They cause damage by puncturing the grape skin during feeding, often leaving a ring of broken grape skin. Aside from damage to the grape berry itself, this can lead to *Botrytis cinerea*, or bunch rot and other fungal disease (Bailey *et al.* 1997). Damage from *B. cinerea* may cause significant losses in grape production, for example losses in New Zealand may exceed 20% under favourable conditions, in very wet seasons complete losses of crops can occur before harvest (Nicholas *et al.* 1994). In one study in New Zealand, *E. postvittana* were introduced to grape bunches at monthly intervals, and the subsequent damage was calculated to determine the percentage weight loss caused by different levels of infestation. Infestations of 5% and 30% of bunches were calculated to cause weight losses of 0.6% and 3.6% respectively (Lo and Murrell 2000).

The adult moths have a wingspan of 10mm and are pale brown, although males have darker markings on the hind portion of their forewings and are smaller than female

moths. The female will lay 'egg masses' of up to 80 eggs on the upper surfaces of grape vine leaves after mating, for her lifespan of up to 14 days (Danthanarayama 1975). After hatching, the larvae source feeding sites throughout the grape bunches and will sometimes spin protective webs around themselves while feeding, making usual methods of control of this pest more difficult; the webs act as a barrier to pesticide.

Insect predators that attack leafrollers include ladybird beetles, spiders, lacewing larvae, predatory wasps and earwigs (Scarratt 2005). Of the parasitoids, *Dolichogenidea tasmanica* Cameron (Hymenoptera: Braconidae) is the most common parasitoid to attack *E. postvittana* (Berndt 2002). Very little is known of the biology of this species (Scarratt 2005) other than its efficiency as an endoparasitoid of *E. postvittana*. The female wasp lays a single egg inside the leafroller larva, which continues to grow inside until the wasp larva reaches the 4th instar, killing the *E. postvittana* larva upon emergence.

To date there has been a substantial body of work examining the effects of understory habitat management on the biological control of leafrollers in New Zealand. Availability of flowering buckwheat (*F. esculentum*) (Scarratt 2005) and alyssum (*L. maritima*) (Berndt *et al.* 2006) can increase fecundity and longevity and consequently also the proportion of female offspring of *D. tasmanica*. Parasitism rates and leafroller densities increase and decrease respectively in vineyards with buckwheat and alyssum between the rows (Scarratt 2005, Irvin *et al.* 2006), although increased parasitism rates and/or decreased pest densities has not been achieved in all trials (Berndt *et al.* 2002, Berndt *et al.* 2006).

Frank *et al.* (2007) used video monitoring of sentinel leafroller larvae baits in vine canopy and on the ground with success in a vineyard in New Zealand. They found the European earwig (*Forficula auricularia* L. (Dermaptera; Forficulidae) to be the most effective (and only) predator of *E. postvittana* in the vine canopy, consuming the same amount of leafroller larvae as the six predator taxa did on the ground.

Grassgrub beetle

The larvae of the grassgrub, *Costelytra zealandica* (White) (Coleoptera: Melolonthinae), can be devastating pests of permanent pasture in New Zealand and can cause severe damage in fodder and cereal crops (Chapman 1984). Damage also occurs when the larvae feed on the roots of grapevines (Mundy *et al.* 2005). The adult beetle is a significant pest of various horticultural crops such as grapes, blueberries and kiwifruit (East *et al.* 1983), where it consumes newly emerged foliage and developing florets during spring.

C. zealandica is a small melolonthid beetle with a one-year life cycle. It overwinters as a larva and apart from brief evening flights as an adult, passes its life in the superficial soil layer. The emergence of adults usually begins mid-October, reaching its peak in November. This lasts approximately eight weeks. Adults may, however, be present as early as September or as late as May (Miller 1921). The adults lives for about three weeks (Fenemore 1966) and transformation from pupa to adults takes place some time before emergence. Females are usually mated as soon as they appear on the surface of the pasture and oviposition takes place two to three weeks after. They will lay their eggs close by, so infestations usually stay localized. However, some females may only lay some of their eggs where they emerged, and fly somewhere else to lay more (Fenemore 1966).

C. zealandica has two endemic natural enemies in New Zealand. A parasitoid, a tachinid fly *Procipto cana* (Hutton) (Tachinidae: Diptera) which lays its eggs in the larvae of *C. zealandica* (Merton 1982) and the non-spore forming bacteria *Serratia* species, which causes amber disease in the larvae (Jackson *et al.* 1993, 2001). *P. cana* can achieve 20% parasitism of grassgrub in high country grassland but is absent from extensive lowland pasture (Merton 1982). Pathogenic strains of *Serratia* spp. contain a specific plasmid (Hurst *et al.* 2000) and ingestion by *C. zealandica* larvae causes death by starvation, as the larvae cease to eat. The bacterium *Serratia entomophila* (Enterobacteriaceae), marketed as the commercial biocontrol product 'Invade®' has been used for grassgrub control in pastures for almost a decade. For protection of pastures, a bacterial suspension is injected into the soil using a modified seed drill and the applied bacteria establish a cycle of amber disease in the treated grassgrub population, reducing the pest population and therefore, the level of pasture

damage (Jackson *et al.* 1992). A novel granular formulation of *S. entomophila*, ‘Bioshield™’, can be effective in reducing populations of grass grub larvae (Townsend *et al.* 2004). These offer prospects for biological control of grass grub larvae; however, the adult beetles have no such natural enemies with the potential to reduce the population feeding on vine leaves.

European earwig

The common earwig *F. auricularia* is a polyphagous omnivore, and while in the past sometimes considered a pest, is for the most part appreciated as a beneficial predator in several agricultural crops (Helsen *et al.* 1998, Solomon *et al.* 2000). Earwigs are key predators of pests with economic importance, capable of maintaining several pest species below economic thresholds, such as woolly aphids (Stap *et al.* 1987, Touns *et al.* 2007, Mueller *et al.* 1998), scale insects (Karsemeijer 1973) and aphids (Carroll *et al.* 1985). Earwigs have also been shown to be efficient predators of leafroller larvae. In a recent study in New Zealand, Frank *et al.* (2007) showed that predation of *E. postvittana* larvae was 50-60% per night, and earwigs were the most effective predators.

Earwigs are univoltine, progressing through four juvenile stages in spring to reach adulthood by summer (Helsen *et al.* 1998), pairing up and mating in autumn and hibernating over the winter. The females lay about 50 eggs and look after the larvae until they reach the second instar. Univoltine organisms such as earwigs are particularly susceptible to agricultural management such as pesticide use, and a single large-scale loss of population can have longer-term repercussions (Miliczky *et al.* 2000), usually increasing problems with key pests (Sauphanor *et al.* 1994).

As effective as earwigs are as biological control agents, observations show that earwig populations can vary greatly within and between growing seasons (Moerkens *et al.* 2008). Most earwig sampling strategies rely on earwigs’ making use of provided shelter, such as corrugated cardboard around tree trunks and posts (Dent 1995). Earwigs hide readily in artificial refuges due to their aggregation pheromone and thigmotactic behaviour (Walker *et al.* 1993). Grape bunches also provide the earwig with shelter, and during the grape growing season, they can be found in grape bunches (Frank *et al.* 2007, Schuster *pers. comm.* 2008).

Harvestmen

Phalangium opilio (Arachnida: Opiliones) is one species of many Opiliones and is most common of the Opiliones species in disturbed habitats, such as crops. In parts of North America two or more generations may be produced, and eggs, juveniles and adults will overwinter. Eggs are laid in damp, protected areas i.e. under rocks and in cracks in the soil, and hatch according to temperature; from three weeks to five months in cold environments (Clingenpeel and Edgar 1966).

P. opilio is considered an effective member of an assemblage of generalist predators that exist in many crops and that together can be effective at keeping pest populations (Dixon and McKinlay 1989, Drummond *et al.* 1990). In a two-year study of generalist predators in Kentucky soybean fields, Pfannenstiel (1995) found that the ‘Phalangidae’ accounted for 13.4% and 17.6% of predation observations of *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) eggs in 1993 and 1994 respectively. That study found these percentages only exceeded by *Nabis* spp. (Hemiptera: Nabidae) and *Geocoris punctipes* Say (Hemiptera: Geocoridae). In a similar study, ‘Opiliones’ were responsible for 39.0% of observed predation events on *H. zea* eggs in Kentucky soybean fields, second only to *Nabis* spp. (Anderson 1996). In those studies, all of the observed predation events by Opiliones spp. occurred at night. While it is not known which Opiliones spp. were responsible for the predation events on *H. zea* eggs in Kentucky soybean, *P. opilio* accounted for >90% of the adult opilionids captured in soybeans in Kentucky (Newton 2000).

P. opilio have been found to have a ‘commensal’ relationship with predatory mites; where a blowfly egg was pierced by feeding mites, *P. opilio* was more attracted and consumption of the eggs was 62 times more than unpierced eggs (Merfield *et al.* 2004). Frank *et al.* (2007) found *P. opilio* to be a predator of *E. postvittana* larvae in a vineyard in Canterbury, New Zealand. In that study, *P. opilio* made the most visits to sentinel larvae baits; however, they only accounted for 7% of successful attacks, where earwigs and spiders were most successful.

In addition to pest arthropods, may feed on dead insects and other decaying material, as well as earthworms, other harvestmen, spiders and other beneficial invertebrates (Edgar *et al.* 1990). Cannibalism and very generalist feeding habits may appear to

reduce the value of; however, these tendencies may allow it to persist in a crop during periods of low pest density, and help suppress outbreaks of pests in their early stages of the season (Schmaedick, unpublished).

1.4.2.1 The ‘sentinel’ species selected for assessing field predation rates

H. zea is not a pest in vineyards; however, is a useful model species for comparison, and were also used as sentinel egg baits in predation experiments (Chapters 3-5). In this context, new vineyard pests which do lay single eggs on leaves and fruit as *H. zea* does, are emerging in North America so using *H. zea* in New Zealand vines can anticipate, to some extent, the role that invertebrate predators may play in reducing populations of these pests should they colonise New Zealand in the future. Such pests include the glassy-winged sharpshooter (*Homalodisca coagulata*) (Hoddle 2003), the spotted-winged Drosophila (*Drosophila suzukii*) (Steck *et al.* 2009) and the European grape moth (*Lobesia botrana*) (Thiery *et al.* 2005).

1.4.3 The New Zealand Wine industry

Approximately 29,000 hectares of wine grapes are planted in New Zealand, and New Zealand wines are readily available to overseas markets (www.nzwine.com) and New Zealand is becoming increasingly competitive. To continue with this success and growth, innovative methods of promoting these wines have been necessary. New Zealand wines are internationally marketed as ‘green’, and as local consumers become increasingly aware of processes involved in producing wine, this ‘green’ image is becoming just as important for domestic as well as international markets. In support of maintaining the ‘clean green’ marketing angle, the Sustainable Winegrowing New Zealand® (SWNZ) (www.wineinf.nzwine.com) framework provides information about economically and environmentally sustainable viticultural practices, including selective use of pesticides, and habitat management to help the establishment of beneficial insects into the area (Crosse 1998). The SWNZ programme has been adopted on over 80% of the producing area, and in October 2008 the 1000th vineyard signed onto the programme (Media release 24 October 2008 www.nzwine.com).

1.5 Aims

In this thesis the influence of non-crop vegetation on predation of pests is examined experimentally at the landscape and local scales in vineyards, using traps and sentinel egg baits in vines. The overall aim is to explore how non-crop vegetation contributes to biological control through ‘bottom up’ processes with pests and ‘top down’ processes through predation, and assess any influence the two spatial scales may have. The objectives of the experiments described in Chapters 2-5 are to find answers to the following questions:

Chapter 2: Do shelterbelts reduce grassgrub abundance in vines at the landscape scale? Do shelterbelts reduce grassgrub abundance in vines at the local scale? What other types of non-crop vegetation influence grassgrub abundance in vines at the landscape and local scales? What influence does the landscape and local scale non-crop vegetation have on *E. postvittana* incidence?

Chapter 3: Does the complexity of non-crop vegetation influence the rate of predation of two different sentinel egg baits on the ground or in the vine canopy at the landscape scale? What non-crop vegetation components of the landscape affect the predation rate of two different sentinel egg baits on the ground or in the canopy?

Chapter 4: Does the complexity of non-crop vegetation influence the rate of predation of two different sentinel egg baits on the ground or in the vine canopy at the local scale? What non-crop vegetation components of the local scale affect the predation rate of two different sentinel egg baits on the ground or in the canopy? With regard to the experiments in Chapter 3, does a synergistic relationship between landscape non-crop vegetation and local non-crop vegetation exist and influence the predation rate?

Chapter 5: What predators are taking the sentinel egg baits? Is there a difference in predators between different intensity habitat management strategies? Does non-crop vegetation influence types of predators in the vine block? Does non-crop vegetation influence the rate of predation of two types

of sentinel egg baits? Does a high intensity habitat management strategy influence the predation rate compared to a lower intensity habitat management strategy?

Chapter 2:

The impact of landscape features on pest abundance in the Waipara valley

2.1 Abstract

Natural enemy dynamics at the landscape scale have been well documented; however, there may be landscape scale effects that relate to the abundance of the pest. In Waipara valley vineyards in Canterbury, New Zealand, grassgrub adults' (*C. zealandica*) feeding flights can result in them feeding directly on new growth on the vines, which can be detrimental to grape yields for up to two years following (Dufour *pers. comm.* 2008, Holding *pers. comm.* 2008). Light brown apple moth (*E. postvittana*) is another pest of economic importance in vineyards, causing damage itself by feeding on grapes but also potentially facilitating infection by *Botrytis cinerea* (see Chapter 1) in the process.

Understanding the influence of the surrounding landscape on the abundance of these two vineyard pests in the Waipara valley winegrowing region is investigated in this chapter, where the aim was to assess the impact on these pests of vegetation in both the surrounding landscape and directly adjacent to the vines. Radii of 500m around each of 25 vineyard-block baiting sites were analysed using ArcGIS to measure areas of non-crop vegetation. A principal components analysis (PCA) was carried out to identify any areas of land use in the landscape that may be responsible for the majority of the variation in numbers of *C. zealandica* caught in traps. There were significantly more *C. zealandica* beetles in traps near shelterbelts at the landscape scale. This was also reflected in the local variables; there was a significantly higher number. of *C. zealandica* caught in traps in vine blocks directly adjacent to shelterbelts. There were not enough data to be able to discern changes in *E. postvittana* numbers.

2.2 Introduction

For biological control to be effective, the pest population needs to be reduced to below an established economic threshold (Gurr *et al.* 2000). Gurr *et al.* (2007) emphasized the importance of assessing the effect of habitat manipulation strategies on pest populations to evaluate the success of conservation biological control (CBC). However, few studies have included the effect of the landscape specifically on the pest populations of agricultural landscapes. There are many studies on the effect landscape structure has on the predation and parasitism of pests by natural enemies (Landis and Marino 1999, Thies and Tscharntke 1999, Bianchi *et al.* 2005, Bianchi *et al.* 2006, Gardiner *et al.* 2009); however, there may be effects at the landscape scale that specifically relate to the phenologic abundance of a particular pest, without invoking the role of the landscape on natural enemy/pest dynamics.

Most recently, Logan *et al.* (2011) found more native cicadas, (*Amphipsalta cingulata* Fabricius (Hemiptera: Cicadidae)) in kiwifruit orchards in New Zealand near modified coastal landscapes, and another native cicada (*Amphipsalta zelandica* Boisduval (Hemiptera: Cicadidae)) was more prevalent in native forest when compared to other types of landscape. In a multiscale landscape approach, O'Rourke *et al.* (2011) found the corn pests European corn borer (*Ostrinia nubilalis* Hubner (Lepidoptera: Crambidae)), Western corn root worm (*Diabrotica virgifera virgifera* (Coleoptera: Chrysomelidae)) and Northern root corn worm (*Diabrotica barberi* (Coleoptera: Chrysomelidae)) incidence increased in simple landscapes. A New Zealand example, *C. zelandica* (grass grub) spends the larval stages of its lifecycle in pasture soil (Given 1966); however, the adult beetles emerge to fly to the nearest palatable vegetation (Townsend *pers. comm.* 2008), which in the case of the Waipara valley landscape is often new growth foliage on vines (Dufour *pers. comm.* 2008).

Although habitat management at a larger landscape scale can improve predation and parasitism of herbivores (Landis and Marino 1999, Thies and Tscharntke 1999, Holland and Fahrig 2000, Ostman *et al.* 2001, Bianchi *et al.* 2005, Bianchi *et al.* 2006, Gardiner *et al.* 2009) and this has been shown effective in the management of *E. postvittana* (Begum *et al.* 2003, Berndt *et al.* 2006), there is limited potential for the use of natural enemies of *C. zelandica*. A tachinid fly, *Proscisso cana* (Diptera:

Tachinidae), has been shown to parasitise the larvae (Thomas 1963), but outside the laboratory significant populations have been found only in in the Canterbury (New Zealand) high country where it parasitises up to 20% of larvae (Merton 1982). It is very rarely found on the Canterbury Plains, as the adult is summer active and therefore can parasitize only third-instar larvae in a 2-year life cycle which occur most frequently in higher altitude grasslands (Jackson and Klein 2006). The Waipara valley is considered to be lowland; within the Canterbury Plains, and therefore it is unlikely that *P. cana* would have an effect on populations of *C. zealandica* beetles.

Currently, attempts at biological control of *C. zealandica* are mostly via *S. entomophila* or *Serratia proteamaculans* (Enterobacteriaceae) that cause ‘amber disease’, a chronic infection of the gut of the larvae (Jackson *et al.* 1993). This disease affects only the larvae however, which in Waipara are most often in neighbouring pastureland, rather than in vineyards themselves, although individual vineyards may have remnant populations ‘inherited’ from previous land use (Holding *pers. comm.* 2008). The commercial biocontrol products (e.g. Invade®) based on these bacteria have been in the marketplace for almost a decade but inconsistent efficiency and high cost have led to limited market penetration (Jackson *et al.* 1999) .

Understanding the effect of the surrounding landscape on abundance of two vineyard pests in the Waipara valley winegrowing region is explored in this chapter, using 25 vineyards throughout the valley. This approach has the potential to exploit this understanding of the landscape factors influencing grass grub beetle incidence in vines. There are no studies on the effect of the surrounding landscape directly on *C. zealandica* adults in vineyards, and very few on this topic, albeit addressing only local scale vegetation, specifically focusing on *E. postvittana* in vineyards (Begum *et al.* 2006, Berndt *et al.* 2006, Bell *et al.* 2006). However, Östman *et al.* (2001) found that landscapes with abundant field margins and perennial crops were associated with low establishment of the bird cherry-oat aphid (*Rhopalosiphum padi* L. (Homoptera: Aphididae), regardless of agricultural system. Findings by den Belder *et al.* (2002) showed onion thrips (*Thrips tabaci* Lindeman (Thysanoptera: Thripidae)) abundance to be significantly decreased in landscapes with more woodlot areas, and suggests that woodlots may physically restrict onion thrips dispersal, functioning as barriers and preventing colonisation by thrips to crop fields. There is some evidence for this,

albeit for natural enemies e.g., hoverflies (Syrphidae) in farmland (Wratten *et al.* 2003) and carabid beetles (Frampton *et al.* 1995). Similarly, nearby vegetation such as shelterbelts may be an important consideration in managing damage to young foliage on vines from *C. zealandica* beetles, as they may block beetles in their feeding flights; usually a direct line of sight from pasture to vine crop (Jackson *pers. comm.* 2008). Shelterbelts and other non-crop vegetation may also then have an effect on abundance of these pests at the landscape scale, particularly in the Waipara valley where pasture and vineyard are being managed alongside each other. Klug *et al.* (2003) conducted a similar study to that in the present chapter in spinach fields using a 600m radius around each study site for landscape comparison; their results illustrate that specific land use patterns might be responsible for colonisation of spinach fields by polyphagous lepidopteran pest species. This relationship may be extrapolated to devise pest control practices and to develop specific habitat management tactics to reduce *E. postvittana* pest incidence in vineyards.

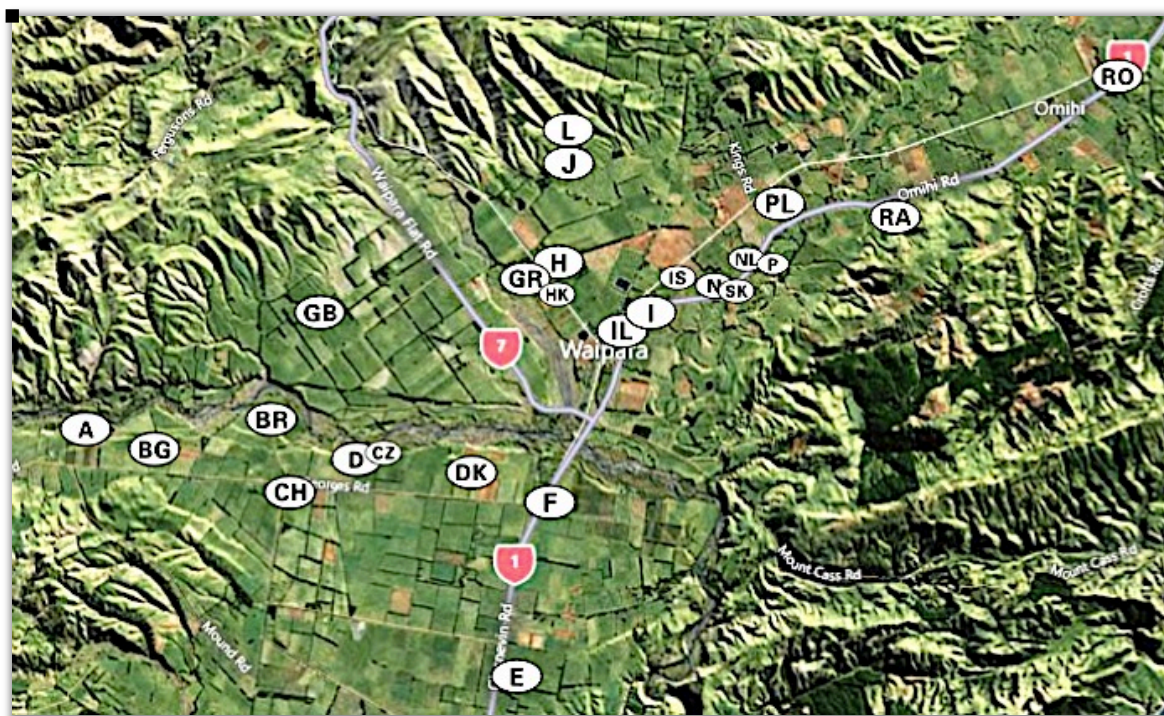
The aim of the work in this chapter was therefore to assess the impact of the vegetation in the surrounding landscape, and that directly adjacent to the vines on the abundance of *C. zealandica* and *E. postvittana* in Waipara valley vineyards.

2.3 Methods

2.3.1 Immigration into vineyards by *C. zealandica*

Adult *C. zealandica* males begin their mating flights approximately two weeks before the feeding flights that result in vine leaf damage begin (Townsend *pers. comm.* 2008). It was determined when the feeding flights were going to start by trapping the males early in October 2008 and 2009 in five of the 25 vineyards used for the study with 'pheromone' traps. Hundreds of *C. zealandica* adults were caught in traps during mating flights, and trapping for feeding adults started two weeks later. The mating flight traps utilised phenol, which mimics the attractant pheromone of adult male grassgrubs (Unelius *et al.* 2008) produced in the beetles as the result of bacterial degradation of tyrosine (Townsend *pers. comm.* 2008). A lure consisting of a resin impregnated with phenol has been widely used to monitor male beetle flight activity. The formula used was made by Richard Townsend of Plant and Food Research Ltd.,

and has been used in pastoral studies of *C. zealandica*. It was placed in weighted 60ml plastic containers, which sat in water, and detergent-filled plastic two-litre ice cream containers. The phenol formulation is highly attractive for the first week in the field, but then loses potency rapidly (Unelius *et al.* 2008). Therefore, *C. zealandica* beetles were emptied from traps weekly, and the phenol replaced to maintain effectiveness. These traps were placed on the ground underneath outer vine rows in 25 vineyards throughout the Waipara valley (see Figure 2.3.1), the trapped beetles to serve as indicators of timing and direction of the feeding flights.



Montana Camshorn	E	Muddy Water	P	Kym Raynor's	I	Pimlico	B R	Waipara Downs	GB
Mudhouse	F	Sherwood Churches	IS	Mairehau	H	The Mound	D K	Sherwood Terraces	J
Waipara Springs	NL	Weka River Omihi	R O	Glenmark Vicarage	N	Concorde	C H	Julian's	L
Greystone	S K	Weka River MacKenzie	G R	Sherwood Stirling	H K	Waipara West	A	Torlesse	IL
Montana Kings Rd	PL	Terrace Edge	D	Fancrest	R A	Dunstaffnage	B G	Sherwood Georges	CZ

Figure 2.3.1: Vineyards in Waipara valley used in this study.

To assess the abundance of *C. zealandica*, directional interception traps (Figure 2.3.2) were used to trap the adult beetles, both male and female, during their feeding flights from approximately mid-October through to late-December 2008 and 2009. The intercepting Perspex sheets were 200mm x 200 mm in height and width and sat in a 9 litre plastic container. The container was nailed onto a post within the vine row, and sealed as they were filled with water, a drop of detergent and 15% monopropylene glycol. The detergent and monopropylene glycol counteracted the water surface tension so the beetles were trapped in the water and could not fly back out.

The monopropylene glycol solution also preserved the beetles to some extent, which is desirable (Wratten *pers. comm.* 2008). Wire mesh was attached to stop birds from eating the trapped beetles.



Figure 2.3.2. Directional interception trap in vine row, Mud House vineyard, Waipara valley.

An assessment of the vegetation growing between the vine inter-rows, and directly under the vines was carried out during the set up of the traps and categories were assigned. These were:

1. Ryegrass that had been left to grow ('ryegrass')
2. Ryegrass mown regularly ('rye-mown')
3. Un-managed weeds ('mixed sward')

The traps were originally engineered to collect *C. zealandica* flying in from four directions; adjacent to the vines, which was possible only until the vines grew around the trap, and from either side of the vine row. *C. zealandica* beetles were collected from the traps every two weeks, unless the weather was much dryer or wetter than usual, when the traps were maintained and emptied as required. The traps were set up in 25 vineyards, the position of the traps was at the growers' discretion; however, each of the two traps at each vineyard were placed in an open area and a sheltered area respectively of the vineyard, in different blocks.

2.3.2 Counts and collection of *E. postvittana* larvae on grape bunches

Twenty-five Waipara valley vineyards were sampled twice for *E. postvittana*, once in February again in March of 2009.

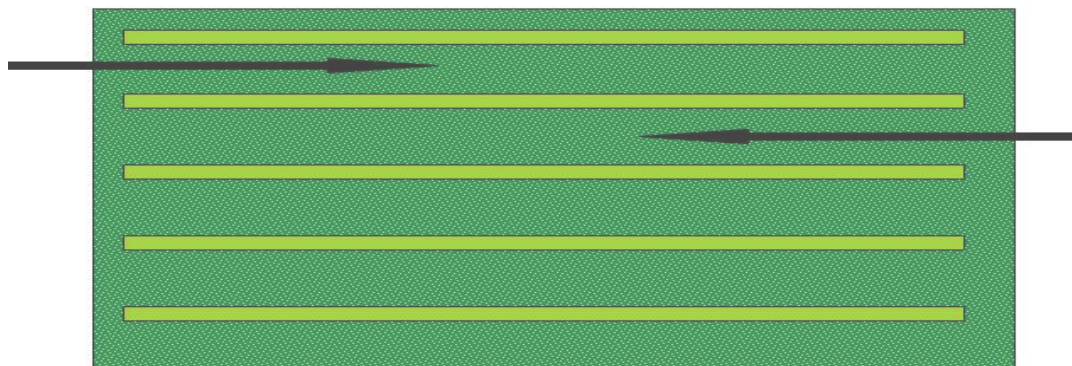


Figure 2.3.2.1 Diagram showing 5 rows in a vine block, arrows indicating direction, from which LBAM larval sampling took place.

Blocks sampled were selected after consultation with the growers. Every fifth row (in blocks at least 20 rows wide) had a minimum of 200 grape bunches examined for *E. postvittana* (Scarratt *pers. comm.* 2009). Every second row assessed was examined from the opposite end of the block toward the centre (Figure 2.3.3).

Vine blocks used for *E. postvittana* abundance assessment also had their vegetation between and underneath the vines categorised in the same manner as for the directional interception trap vine blocks.

2.3.3 Statistical analysis

To quantify the pattern of land use at each site, at the landscape scale, digital photographs of the Waipara valley (<http://www.linz.govt.nz/topography/aerial-images/nztm-geo/bv25>) were acquired from the Land Information New Zealand online orthophoto library (www.linz.govt.nz), and georeferenced in ArcGIS-9 mapping software ([www.esri.com/software/arcgis.com](http://www.esri.com/software/arcgis)). The photographs were taken in 2004/05, so further observations in the vineyards and around Waipara valley were used to ‘ground truth’ the details in the photographs. GPS points taken at each sampling site were added to the software and the landscape was then classified within a 500m radius of the centre of each sampling area into different land cover categories; vines, pasture, scrub, shelterbelts, residential vegetation, crop, industrial, riverbed and water (Table 2.3.3.1).

A 500m radius was used as similar landscape-scale pest abundance studies have demonstrated findings with significant outcomes at less than 1km radii (Thies *et al.* 2003, Bianchi *et al.* 2005). *C. zealandica* is a flying pest and usually larger spatial scales are used for flying arthropods (Thies *et al.* 2003, Bianchi *et al.* 2005) However, local viticulturalists have noted that *C. zealandica* flies directly from neighbouring pasture to the vines (Dufour *pers. comm.* 2008, Holding *pers. comm.* 2009).

The area of each of these categories was calculated in ArcGIS-9 and the categories areas then used as variables in the pest abundance analysis.

Table 2.3.3.1 Different categories of landscape areas around the Waipara valley and how they were defined.

Landscape variable	Definition
Vines	Vine rows, both productive and non-productive
Pasture	Grass and tussock in usually large open spaces, either grazed or with no stock
Scrub	Patches of Matagouri (<i>Discaria toumatou</i>) and other bush species, both native and exotic
Shelterbelts	Long thick 'hedges' of usually either <i>Pinus radiata</i> or <i>Cupressus macrocarpa</i> , along the sides of agricultural areas or near residences
Residential vegetation	Any low-disturbance-managed area of vegetation adjacent to houses (vegetation gardens for personal use were not included)
Crops	Any crop that was not grapevine but was cultivated.
Industrial	Areas with no vegetation, associated with businesses, usually concrete and gravel
Riverbed	The Waipara river (as it is 'braided' the areas with water were included)
Pond	Standing water

The software 'R' (R Development Core Team (2008). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org>), was used to produce a principal components analysis (PCA). A PCA was used to try to reduce the set of potentially correlated landscape variables into a set of uncorrelated variables called principal components. As the PCA did not assist in explaining variation in the data, a correlations analysis using GenStat software (<http://www.vsnl.co.uk/software/genstat>), revealed the uncorrelated variables: 'residential vegetation' i.e. gardens etc., 'shelterbelt', 'scrub' and 'pasture' (Table 2.4.3). Variables were transformed to have standardised means so that they could be compared in the analysis with equal weighting. The variable 'water' (a composite of 'riverbed' and 'pond') was taken out of the analysis, as there were not enough data. Uncorrelated variables (pasture, scrub, shelterbelt, residential vegetation) were used in the final generalised mixed model (GLMM) analysis.

The number of *C. zealandica* captured in each trap throughout the sampling period fitted a negative binomial distribution. Consequently these data were analysed using a generalised linear mixed model (GLMM) with a logarithm link. A fixed model was used for the location of the traps, 'location', and the uncorrelated variables. A random model was used for 'vineyard' and 'time'.

The direction from which the *C. zealandica* beetles flew into the interception traps could not be accurately defined due to high winds and vine growth obscuring some traps, so this variable was not used in the analysis. The vegetation categories beneath and between the vine inter-rows were not included in the GLMM analysis as they were correlated variables.

There were not enough data to measure or analyse the abundance of *E. postvittana* larvae with any level of confidence (a mean of 0.01 larvae/grape bunch).

2.4 Results

The initial PCA revealed that PC1 and PC2 accounted for 49% of the variation (25% and 24% respectively) and PC3 accounted for a further 18% (Table 2.4.1). Of the landscape variables correlated with PC1-3, only those loadings greater than 0.4 (Hatcher & Stepanski 1994) were considered (Table 2.4.2) as lesser loadings accounted for very little variation.

Crops and shelterbelts were negatively correlated with PC1, while crops and grapevines were positively correlated with PC1. Pasture was negatively correlated and grapevines positively correlated to PC2, and scrub was very negatively correlated with PC3. This makes naming the two principal components used in figure 2.4.1 difficult to define with accuracy, particularly as the variable 'grapevines' strongly positively correlates (>0.4) with both PC1 and PC2. Also, there is no obvious steep slope in the scree plot, which would clearly depict which components could be considered as being important (Figure 2.4.2) compared to other components.

Correlations analysis (Table 2.4.3) between the standardised means of the landscape variables found only four variables to be uncorrelated: ‘residential vegetation’, ‘scrub’, ‘pasture’ and ‘shelterbelts’.

Abundance of *C. zealandica* adults was not significantly different in the shelterbelt location compared with the open vine block location in the 2008/2009 season (Table 2.4.4). None of the non-correlated landscape variables had a significant effect on the abundance of beetles caught in the traps (Table 2.4.4).

There was also no significant effect of the landscape variables ‘pasture’ and ‘scrub’ in the 2009/2010 season; however, there were significantly more ($P < 0.05$) *C. zealandica* beetles in traps near shelterbelts at the landscape scale. This was also reflected in the local variables (‘open’ or ‘shelterbelt’); there was a significantly higher number of *C. zealandica* ($P < 0.01$) caught in traps in vine blocks directly adjacent to shelterbelts (Table 2.4.4).

There were no significant interactions between any of the variables; therefore they have not been included in the final models (see Table 2.4.4).

In the second season (2009/2010) of abundance assessments there were less than half the number of *C. zealandica* beetles caught than in the first season (2008/2009), either in the open vine blocks or in vine blocks next to shelterbelts (Figure 2.4.3).

Fewer *C. zealandica* beetles were caught in traps when the ‘open’ or ‘shelterbelt’ trap was in a vine block that had mown ryegrass, and even fewer when ryegrass was left to grow, than in vine blocks with mixed sward between the vine inter-rows (Figure 2.4.3). These numbers can be compared only visually as the variables were correlated and cannot be accurately statistically tested.

Landscape scale effects of different vegetation on predation in vineyards

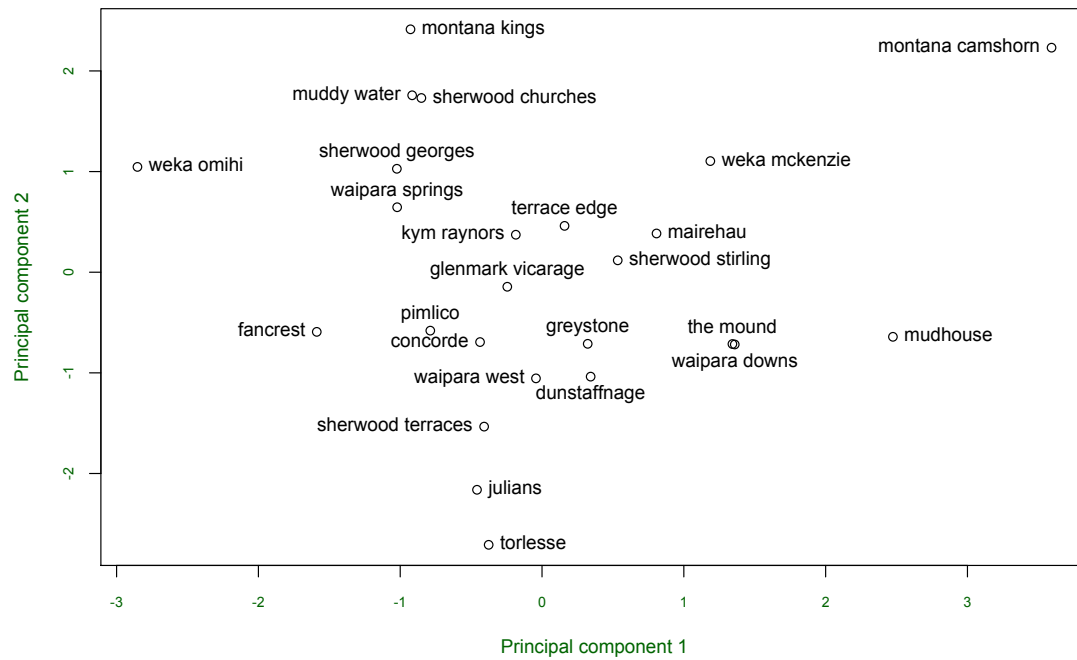


Figure 2.4.1 Principal components analysis plot showing the relationship the 2 principal components have with vineyards in the Waipara valley.

Table 2.4.1 Principal components analysis variance matrix showing the proportion of variance in the data accounted for by each principal component (2 d.p.)

	Importance of components						
	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Standard deviation	1.32	1.30	1.12	0.99	0.93	0.64	0.09
Proportion of variance	0.25	0.24	0.18	0.14	0.12	0.06	0.01
Cumulative proportion	0.25	0.49	0.67	0.81	0.93	0.99	1.00

Table 2.4.2 Principal components analysis loadings matrix showing the correlations (2 d.p) between each landscape variable and the first three principal components. Stronger correlations (>0.4, positive or negative) are shown.

	Component loadings matrix		
	PC1	PC2	PC3
Crops (non-vine)	-0.44		
Industrial areas	0.56		
Pasture		-0.71	
Residential vegetation			
Scrub			-0.83
Shelterbelts	-0.44		
Grapevines	0.53	0.48	

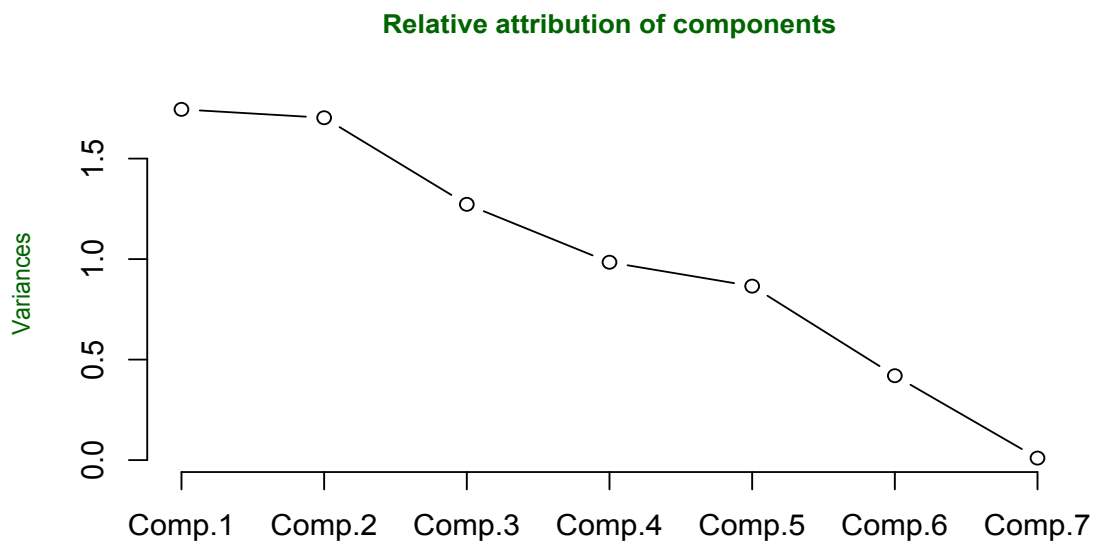


Figure 2.4.2 Scree plot derived from the PCA, comparing components' relative influence on vineyards

Table 2.4.3 Correlations analysis showing standardized and uncorrelated landscape variables

Landscape variable:				
Residential veg_st	-			
Shelterbelt_st	-0.0125	-		
Scrub_st	-0.2023	0.1422	-	
Pasture_st	0.0883	-0.2821	-0.0973	-

Table 2.4.4 Generalised linear mixed model (GLMM) analysis for adults of *Costelytra zealandica* in vine blocks in 25 vineyards in Waipara valley. Location = the effect of position in the vine block (next to shelterbelt or centre).

	Factor	Wald statistic	n.d.f	P-value	Level of significance
<i>Costelytra zealandica</i>					
2008/2009					
	Location	1.65	1	0.212	NS
	Pasture	1.85	1	0.189	NS
	Scrub	0.94	1	0.385	NS
	Shelterbelt	0.15	1	0.703	NS
	Residential vegetation	0.01	1	0.939	NS
<i>Costelytra zealandica</i>					
2009/2010					
	Location	9.80	1	0.005	**
	Pasture	0.00	1	0.946	NS
	Scrub	0.61	1	0.443	NS
	Shelterbelt	5.47	1	0.030	*
	Residential vegetation	0.03	1	0.863	NS
<i>Costelytra zealandica</i>					
Both seasons					
	Location	6.18	1	0.020	*
	Pasture	2.33	1	0.143	NS
	Scrub	0.03	1	0.863	NS
	Shelterbelt	0.89	1	0.360	NS
	Residential vegetation	0.05	1	0.833	NS

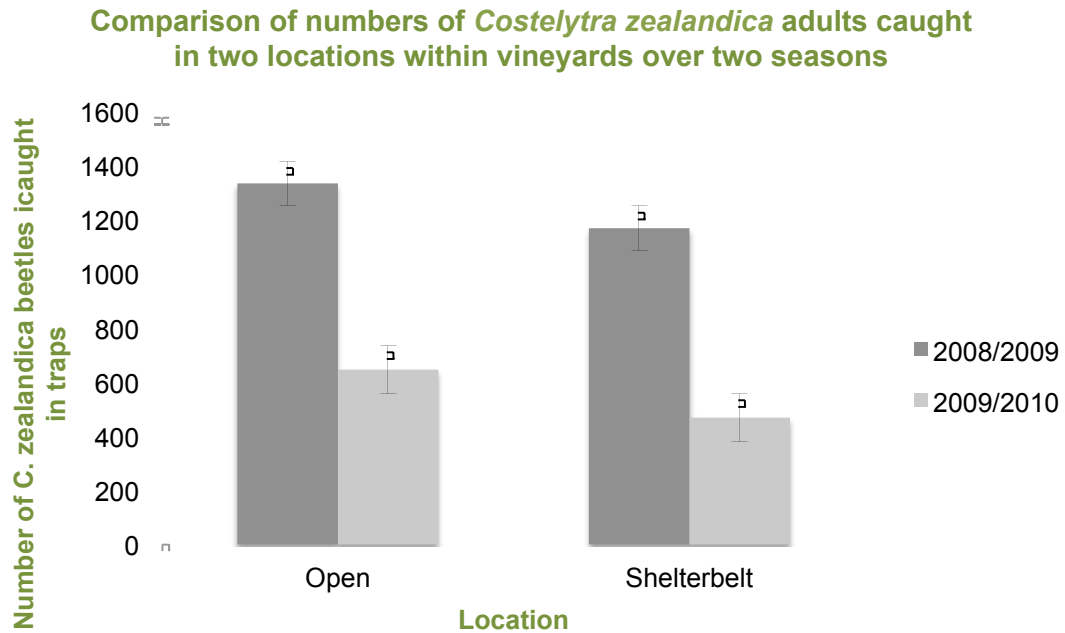


Figure 2.4.3 The mean number (\pm SE) of *C. zealandica* adults caught in traps in two locations ('open'= within the vine block and 'shelterbelt'=adjacent to a vine block), in two summer seasons (November-January 08/09 and 09/10) in 25 vineyards.

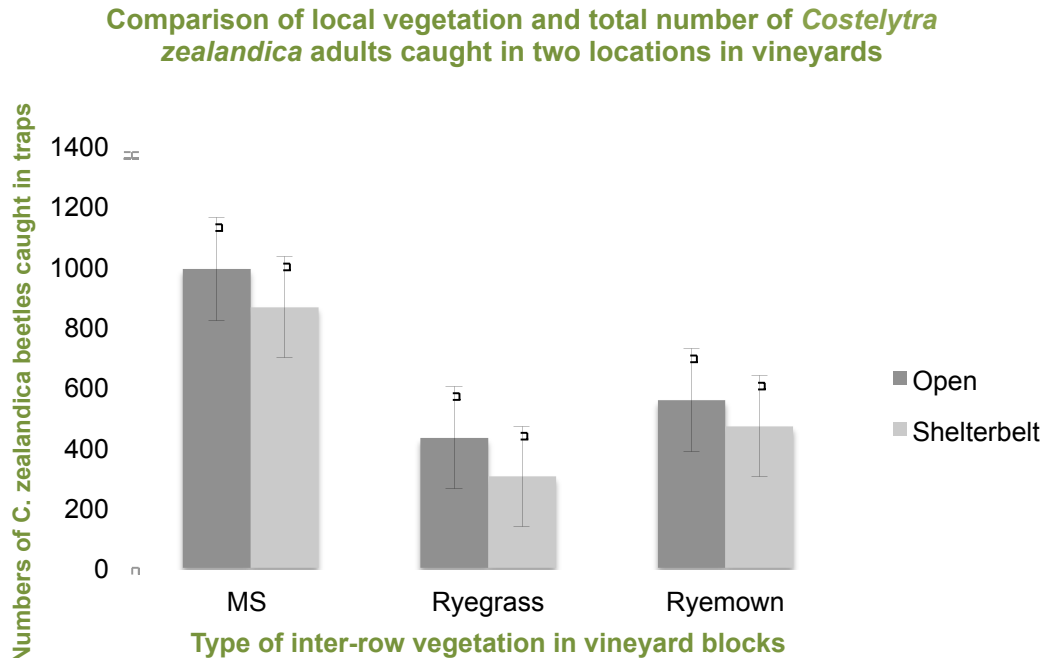


Figure 2.4.4 The mean number (\pm SE) of *C. zealandica* adults caught in traps in vineyard blocks with different inter-row vegetation in 25 vineyards over two summer seasons (Nov-Jan 08/09 and 09/10 together). MS = mixed sward, Ryegrass = ryegrass, Ryemown = mown ryegrass. Traps were set in either an 'open' vineyard block, or near a 'shelterbelt'.

2.5 Discussion

The abundance of *C. zealandica* adults was significantly lower ($P < 0.05$, Table 2.4.4) in traps in vine-blocks near shelterbelts at the landscape scale, and highly significantly lower ($P < 0.01$, Table 2.4.4) at the local (field) scale in the 2009 season (October – December). While the first field season (October – December 2008) did not show any significant results, there was still a pronounced pattern of lower abundance of *C. zealandica* caught in traps in vine blocks near shelterbelts compared to exposed, open areas of vine blocks (Figure 2.4.3). Several studies have shown that movement rates of insects are greatly reduced on encountering a border between host plants and non-host plants, and that this effect is strengthened with increasing height of the non-host vegetation (Lawrence 1982, Capinera *et al.* 1985, Power 1987, Bohlen and Barrett 1990, Frampton *et al.* 1995, Holmes and Barrett 1997, Wratten *et al.* 2003). Woody borders such as shelterbelts have been shown to slow or stop movement of various insects from neighbouring crop fields and/or from more distant points in the landscape (Lewis 1969, Hawkes 1973, Bowden and Dean 1977, Fry 1997, Mauremooto *et al.* 1995). On a larger scale, such barriers to movement may further reduce regional populations of crop insects by limiting movement between crop fields.

The local non-crop vegetation grown amongst the vines may also have some effect although it is not clear what the mechanism could be. Traps in vine-blocks with ryegrass left unmown, rather than a mixed weedy sward (usually sparse) or where ryegrass was mown in between vine-rows seem to have had lower numbers of *C. zealandica* beetles overall (Figure 2.4.2), although this is not included in the analysis and is therefore speculation. Tsitsilas *et al.* (2006) observed lower numbers of pest arthropods in pastures adjacent to shelterbelts with tall grass in several areas. Notably, in those areas there was also greater abundance of predatory mites and spiders.

An increase in natural enemy numbers with habitat diversification such as that provided by field margins or inter-row plantings is well documented (Landis *et al.* 2000, Nicholls *et al.* 2001, Berndt *et al.* 2006), although much of this research has

focused on predatory Coleoptera such as carabids and staphylinids (Wratten 1988, Dennis *et al.* 1994, Thomas and Marshall 1999, Holland and Luff 2000). However, it is not likely that an increased abundance of predators could be responsible for the lower numbers of beetles caught in traps (present study) in these areas with unmown ryegrass, as the beetles fly in to the vines directly from adjacent pasture unless impeded, and feed on the new foliage and there are no known predators of the *C. zealandica* beetle other than birds.

Woody borders such as shelterbelts have also been shown to enhance crop pest populations, limiting their movement out of the crop by acting as barriers, thus trapping them within the fields and promoting local population build-up. Dix *et al.* (1997) found that Coleoptera species were more abundant in muskmelon crops in Eastern Nebraska in exposed plots than near shelterbelts.

2.5.1 Prospects for biological control using local and landscape 'barriers' against *C. zealandica* and *E. postvittana*

Growers often spray edges of vine blocks when trying to manage *C. zealandica* because the beetles are considered to be from adjacent pasture (Dufour *pers. comm.* 2008, Holding *pers. comm.* 2008, Townsend *pers. comm.* 2008). The lower numbers of beetles found in vines near shelterbelts suggests such control measures may not be needed if shelterbelts can be effective in keeping beetles below an economic threshold.

Maintenance of woody borders is desirable for insect pest management. However, the desirability of these depends on the trade-off between their positive effects on pest populations (increased predation, decreased colonization of new crop fields) and their effects that benefit pest populations (provide complementary habitat, are a barrier to movement resulting in local population build-up). Practicality and cost must be considered also, especially if shelterbelts might shade or compete with vines.

Chapter 3:

The effects of landscape features around vineyards on predation rates of *Epiphyas postvittana* and *Helicoverpa zea* sentinel egg baits.

3.1 Abstract

Landscapes with a greater proportion of non-crop vegetation may increase pests' natural enemies' efficiency in reducing pest populations.

This chapter aims to evaluate the hypothesis that higher complexity, that is, more non-crop vegetation of different types in the surrounding landscape will lead to a higher predation rate. Sentinel egg baits of *E. postvittana*, an important vine pest in Australasia, and *H. zea*, a pest in other agricultural systems and a good model species for other types of vine pests, were used in vines to determine predation rates in vineyards across the Waipara valley, Canterbury, New Zealand landscape.

Using methods detailed in Chapter 2, a radii of 500m around each of 25 vineyard-block baiting sites were analysed using ArcGIS to measure areas of non-crop vegetation and a principal components analysis (PCA) was carried out to identify any areas of land use (principal components) in the landscape that may be responsible for the majority of the variation of the predation rate. However, no relationships were found and there was no significant effect of the landscape variables on the predation rate. This 'negative' result is important as it points to vineyard-scale factors as likely to be key in spatially differing predation rates. This in turn implies that viticulturalists can potentially manipulate this factor to increase the contribution of biocontrol to reducing variable costs and improved insecticide practices.

3.2 Introduction

In the last decade, scientific reviews have considered CBC principles that can be adopted to habitat management strategies (HMS) (Gurr and Wratten 2000, Landis *et al.* 2000, Gurr *et al.* 2004, Zehnder *et al.* 2007, Jonsson *et al.* 2008, Gurr *et al.* 2012) at the local scale. Also, a number of studies have shown that landscape composition is an important factor that may also contribute to the efficacy of natural enemies (Thies and Tscharrntke 1999, Bianchi *et al.* 2005, Tscharrntke *et al.* 2007, Rand *et al.* 2012), and other ecosystem services (Westphal *et al.* 2003, Fiedler *et al.* 2008). Specifically, natural enemies' efficiency in controlling pests can be higher in landscapes with a greater proportion of non-crop vegetation compared with landscapes poor in non-crop habitat (Thies and Tscharrntke 1999, Thies *et al.* 2003). The degree of disturbance at the landscape scale (cultivation, pesticide use etc.) can also be a factor (Jonsson *et al.* 2010).

In this chapter, the potential to determine effects of landscape composition on predation rates in vineyards is explored. The hypothesis was that higher complexity in the surrounding landscape composition would yield a higher predation rate. There is the possibility that low-disturbance management within vineyards and high-complexity landscape surrounds combined may have a synergistic effect, increasing the predation rate to a level greater than either factor alone (Tscharrntke *et al.* 2005). Therefore Chapter Four investigates HMS at the vineyard scale across Waipara valley in a concurrent study.

In contrast, this chapter uses sentinel egg baiting at a landscape scale for measuring predation rate. Egg masses of *E. postvittana*, an important pest in vineyards all over Australasia, Hawaii and most recently confirmed in California (Suckling & Brockerhoff 2010) were used. Eggs of *H. zea*, which is not a pest in vineyards, but is a useful model species for comparison (see Chapter 1.4.2.1), were also used.

Egg masses of *E. postvittana* are most often laid on the undersides of vine leaves in the canopy; however, the larvae that drop from the canopy, often as a result of disturbance, can suffer high rates of predation on the ground (Glenn and Milsom 1978, Epstein *et al.* 2001). The sentinel egg baits used for this study were pinned on

paper to the undersides of leaves in the canopy, at the height of the grapes, and were also pinned on the ground directly beneath the same vine canopy.

The aim of the work in this chapter therefore was to quantify predation rate in egg masses of *E. postvittana* and *H. zea* eggs across 25 vineyards in the Waipara valley, Canterbury, New Zealand to identify landscape factors affecting the rate of biological control.

3.3 Methods

Predation rate of *E. postvittana* and *H. zea* eggs was quantified in Waipara vineyard blocks at 25 vineyards in Canterbury. Blocks of vines that had not been treated with insecticides were chosen, to exclude possible effects of chemical applications. The same vineyards as those used in Chapter 2 provided study sites, from January until April 2010 (see Chapter 2, Figure 2.3.1).

Filter papers and wax papers containing egg batches of *H. zea* and *E. postvittana*, respectively, were cut into 10mm triangles and 50mm squares. The eggs of *H. zea* were counted and the *E. postvittana* egg masses circled with pencil. Both *E. postvittana* and *H. zea* eggs were obtained from the youngest cultures at Plant and Food Research, Auckland. The strips of paper were then stored at 12C for transport to the vineyards the next day.

In each of the 25 vineyards, four vine plants were chosen in a block; two in the edge row, and two within the block. Initially, 30 vineyards were chosen to maximise sample size for more confidence in the statistical analyses while also being a manageable number of vineyards to work with given the time and resources available. However, due to access restrictions and weather disruptions, five were omitted from the study.

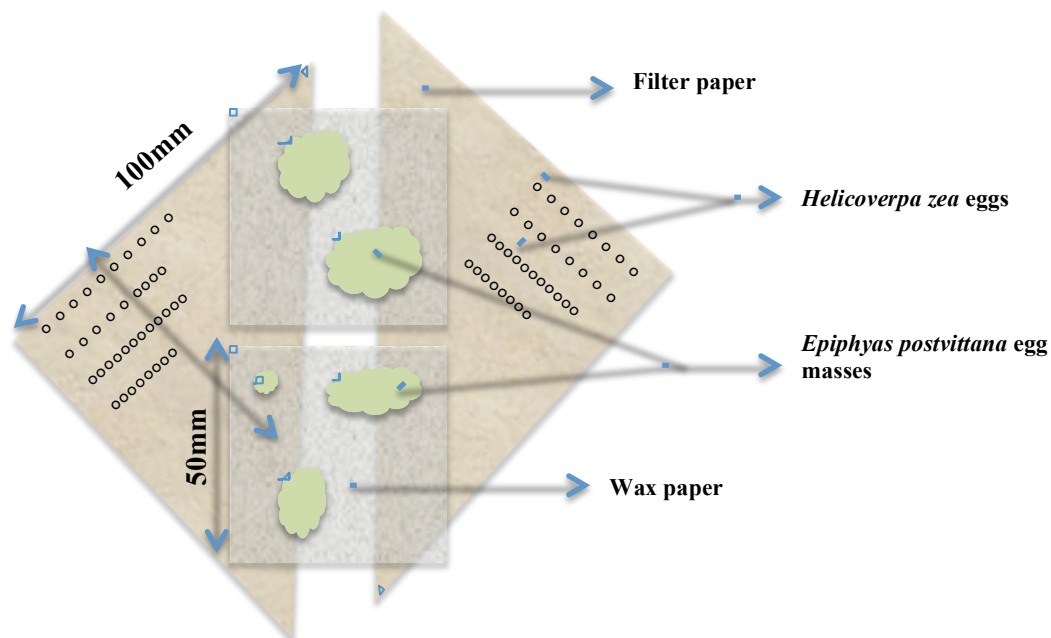


Figure 3.3.1 Sentinel egg bait experiment layout – either on the ground, pegged directly beneath the vine rows, or in the canopy, stapled to undersides of grapevine leaves.

H. zea eggs and *E. postvittana* egg masses were placed initially in the canopy, and then also on the ground, every two weeks for 14 weeks, including a pilot study undertaken to determine how long the eggs should be left out. Two of these sampling times were fruitless in all vineyards due to extremely wet weather conditions. Each time two filter papers of *H. zea* eggs and two wax papers of *E. postvittana* egg masses were stapled to the underside of leaves in the canopy, and two filter papers of *H. zea* eggs and two wax papers of *E. postvittana* egg masses were ‘pegged’ on the ground directly under the vines with wooden toothpicks, at both the ‘edge’ of a vine block, and at least (where possible) five rows into the same block ‘centre’ (Figure 3.3.1). The two types of eggs were together to make sure the same assemblage of predatory arthropods were responsible for any predation. Sentinel egg bait papers were retrieved after four nights, and the eggs remaining counted, visually assessed and collected. Eggs and egg masses were considered predated if missing, not intact or aspirated. This was determined in the field, with a 10x lens at the time of retrieval, to prevent any damage to the eggs in transport back to Lincoln University being mistaken for predation. *E. postvittana* eggs were considered aspirated if they had turned brown and had surface damage such as an entry point, and *H. zea* eggs if the

egg casing was empty, in this case being transparent with an entry point. Any damage was assumed to result in a non-viable egg.

Since the predators likely responsible in these experiments are thought to be non-flying and therefore have lower dispersal rates than other arthropods (Mauremooto *et al.* 1995, Moerkens *et al.* 2010) and vineyards in the Waipara region are closely associated, a 500m radius was considered most appropriate. The areas of each of these classes were calculated within ArcGIS-9 (see Statistical methods 2.3), and then used as variables in the predation rate analysis.

3.3.1 Statistical analysis

The number of *H. zea* and proportion of *E. postvittana* eggs predated throughout the sampling period fitted a binomial distribution. Consequently, these data were analysed using a generalised linear mixed model (GLMM) in GenStat. A fixed model was used for the uncorrelated landscape variables (pasture, scrub, shelterbelt, residential vegetation (Chapter 2, Table 2.4.3), and vineyard and time of collection were included as random effects in each model to account for any spatial and temporal autocorrelation. Interactions between fixed effects (also with the random effects: vineyard and time of collection) were tested, but are not included in the description of the analysis below (Table 3.4.3) as they had no significant effect and therefore did not explain any variation in the predation rate more than the single variable analyses.

Vineyards were included in the analysis as a random effect as differences other than landscape components most likely reflect any differences in management. However, the percentage of total predation of both *H. zea* and *E. postvittana* sentinel egg baits was calculated to compare predation in the different vineyards (Figure 3.4.2).

Local variables (edge of vine rows vs. centre (location), vine understory and between vine vegetation) are included in this model as they are not independent from the landscape variables; however, the influences on predation of local variables are discussed in Chapter 4.

3.4 Results

There were no significant effects on the predation rate of either *H. zea* or *E. postvittana* egg baits on the ground or in the canopy (Table 3.4.3) from any of the uncorrelated landscape variables (pasture, scrub, shelterbelt, residential vegetation). These uncorrelated variables comprise 53% of the defined landscape composition (Figure 3.4.1).

There were differences in the total predation between vineyards; however only a visual assessment can be made as no definitive analysis could be carried out. *E. postvittana* (LBAM) egg baits were most highly predated (42%) at Mairehau vineyard, and least predated at Weka Omihi vineyard (10%). Predation of *H. zea* eggs was highest at Dunstaffnage vineyard (80%) and lowest at Torlesse (54%).

Composition of the Waipara valley landscape

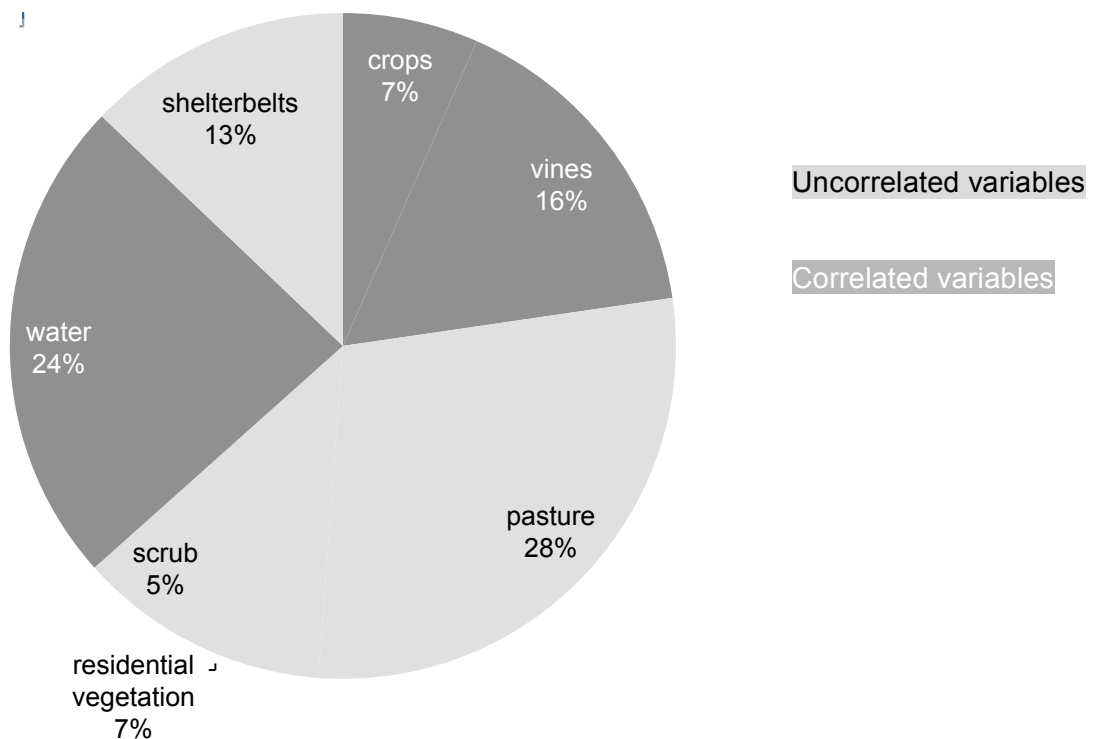


Figure 3.4.1 Pie chart comparison showing the percentage of landscape each variable (component) occupies. Variables shown in the lighter grey are non-correlated and were used in the analysis.

3.4.3 Generalised linear mixed model (GLMM) analysis for *Helicoverpa zea* and *Epiphyas postvittana*, comparing landscape effects of non-vine vegetation on predation in vine blocks in 25 vineyards in Waipara valley. **Local effects (*in italics*) are included as they are part of the landscape, but discussed in Chapter 4

	Factor	Wald statistic	n.d.f	P-value	Level of significance
<i>Helicoverpa zea</i>					
Canopy baits	<i>Location</i> **	24.73	1	<0.001	***
	<i>Between vine</i> **	1.09	2	0.589	NS
	<i>Under vine</i> **	0.85	1	0.363	NS
	Pasture	0.02	1	0.898	NS
	Scrub	2.89	1	0.108	NS
	Shelterbelt	0.00	1	0.957	NS
	Residential vegetation	1.38	1	0.256	NS
Ground baits	<i>Location</i>	23.85	1	<0.001	***
	<i>Between vine</i>	2.67	2	0.286	NS
	<i>Under vine</i>	1.04	1	0.321	NS
	Pasture	0.97	1	0.340	NS
	Scrub	0.01	1	0.919	NS
	Shelterbelt	0.07	1	0.793	NS
	Residential vegetation	0.77	1	0.389	NS
<i>Epiphyas postvittana</i>					
Canopy baits	<i>Location</i>	2.28	1	0.135	NS
	<i>Between vine</i>	0.11	2	0.948	NS
	<i>Under vine</i>	0.33	1	0.571	NS
	Pasture	0.58	1	0.456	NS
	Scrub	0.50	1	0.491	NS
	Shelterbelt	1.26	1	0.277	NS
	Residential vegetation	1.37	1	0.258	NS
Ground baits	<i>Location</i>	26.05	1	<0.001	***
	<i>Between vine</i>	11.77	2	0.009	**
	<i>Under vine</i>	1.17	1	0.293	NS
	Pasture	0.98	1	0.335	NS
	Scrub	0.60	1	0.450	NS
	Shelterbelt	0.09	1	0.765	NS
	Residential vegetation	0.16	1	0.691	NS

3.5 Discussion

3.5.1 Overview

In this chapter, it has been shown that the ability of different landscape 'types' (vegetation, land use) to enhance biological control (BC) through predation was not a function of the diversity of the landscape at the larger spatial scale assessed.

The effect of the surrounding landscape on predation rates was investigated using sentinel egg baiting in 25 different vineyards across the Waipara valley, Canterbury, New Zealand.

3.5.2 The ability of the surrounding landscape to supply biological control

The surrounding landscape provided no influence on the variation in predation rate of either *E. postvittana* or *H. zea* eggs.

Intensification of the agricultural landscape has resulted in striking changes; large landscapes of monocultural cropping, with other vegetation types represented in far smaller and less frequent areas are prevalent, rather than complex landscapes with a large diversity of both crop plants and other vegetation nearby (Bianchi *et al.* 2006). Many studies have shown that more complex landscapes support larger populations of natural enemies and contribute to biological control (Landis and Marino 1999, Thies and Tschardtke 1999, Holland and Fahrig 2000, Ostman *et al.* 2001, Bianchi *et al.* 2005, Bianchi *et al.* 2006, Gardiner *et al.* 2009). However, in a review, Bianchi *et al.* (2006) found that while 45% of studies showed that natural enemy effectiveness and efficiency was higher in complex landscapes, 40% showed no effect at all, and 15% found lower populations of natural enemies in complex landscapes.

Klug *et al.* (2003) and Holland and Fahrig (2000) both reported that forest and woody habitats (respectively) in the landscape (i.e. higher landscape complexity) did not decrease pest pressure in neighbouring crop fields. Thies *et al.* (2005) found that although surrounding landscape complexity increased aphid mortality, it also increased aphid densities, resulting in no difference in pest pressure in potato and cereal crops in simple or complex landscapes. This may be a result of cereal and potato aphids being polyphagous and benefitting from the increased vegetation or alternative host plants. Gardiner *et al.* (2009) suggests that the division of findings

between complex landscapes reducing pest pressure or not shows that particular natural enemy species may respond to the landscape in different ways. In the current work, the spatial scale at which the predators in this study operate may be too small for the larger surrounding landscape to significantly affect them. Of the studies where complex landscapes increased natural enemy populations or activity, a significant proportion use a measure of parasitism (e.g. by parasitoid Hymenoptera species) for specific pests, or a measure of predation by winged predators (Gardiner *et al.* 2009) which is probably a reflection of the larger spatial scale at which flying natural enemies utilise available resources.

In an observational study such as this, determination of a sample size that will show statistically robust effects is guided by previously published research methodology and results, and any relevant preliminary study findings. Therefore it is also important to consider the sample size in this current work (N=25 vineyards). While similar studies show appropriate and significant results (Östman *et al.* 2001, Bianchi *et al.* 2005) with small sample sizes (N=10 farms and N=26 properties, respectively), there are other successful examples using larger sample sizes. For example, Steffan-Dewenter (2003) found an increase in insect abundance at the landscape scale using 45 orchards and Thomson *et al.* (2010) found an increase in the numbers of individuals of several parasitoid families near woody habitat at the landscape scale using 44 vineyards. It may be that this current work needed a larger sample size to reveal a previously undetected landscape scale effect of non-crop vegetation. However, it is unlikely given the significant effects other very similar predation studies found with smaller sample sizes (Östman *et al.* 2001, Bianchi *et al.* 2005). It should be noted that the current work, like Bianchi *et al.* (2005), measured predation rate which is indicative of tangible biological control. In contrast, the work of Steffan-Dewenter (2003) and Thomson *et al.* (2010) above measures only captured/dead insects and there are no biocontrol dynamics quantified.

3.5.3 The predator response

The natural enemies responsible for the predation in the present study may not have landscape scale effects because their dispersal is at a small spatial scale. Schmidt *et al.* (2005) studied spider densities in winter wheat fields at spatial scales from 95m to 3km radius and found that densities of wolf spiders were enhanced by non-crop

habitats at small spatial scales; mostly between 190m-530m, and out of 64 common spider species, more than half were only locally enhanced. While some predominantly ground-dwelling predators such as ‘ballooning’ spiders (Linyphiidae, mainly) can move across large distances (Schmidt *et al.* 2005), most (largely) non-flying predatory species such as mites, harvestmen and earwigs tend towards moving around more locally (Moerkens *et al.* 2010). In this context it is interesting that ‘beetle banks’ in Europe (Wratten *et al.*) enhanced populations of predatory beetles on the banks in winter, followed with emigration into the field in spring; however, in New Zealand such banks acted as all-year refuges for spiders, which do not emigrate (MacLeod *et al.* 2004).

3.5.4 Conclusions

This work in this chapter demonstrates that biological control services provided by generalist predators in North Canterbury wine country are not dependent on the surrounding landscape.

It has been acknowledged that non-crop vegetation in landscapes may not affect predation rates if the overall landscape complexity is high, compared to non-crop vegetation in largely simple landscapes (Tscharrntke *et al.* 2005). It may be that Waipara valley is more complex in comparison to larger, monocultural landscape environments, and therefore is more likely that local non-crop vegetation may influence predation by generalist predator natural enemies. As well, the methodology used in the current baiting work needs to be considered as a factor influencing the above results and conclusions. Only those predators that readily respond to batches of, or single Lepidopteran eggs were implicated in these results (see video work in Chapter 5). Other natural enemy guilds, such as parasitoid wasps, may be more mobile but most species would not have responded to eggs as potential hosts.

In order to ascertain what effects the local non-crop vegetation (such as weedy sward and ryegrass within and surrounding the vineyard blocks) may have on the predation rate of sentinel egg baits, an investigation was undertaken alongside the present study. Chapter 4 therefore addresses the hypothesis that local non-crop vegetation will increase the rate of predation in vineyards.

Chapter 4:

The effects of vineyard habitat management on predation rates of *Epiphyas postvittana* and *Helicoverpa zea* sentinel egg baits.

4.1 Abstract

Habitat management strategies (HMS) provide a platform on which growers can base their implementation of biological control (BC) principles to provide resources for natural enemies.

Frequently disturbed crop areas may have an influx of pests when predators are displaced by management practices such as mowing or herbicide application.

This chapter aims to evaluate the hypothesis that low-disturbance HMS in vineyards (such as between-vine growth left unmown, or fewer or no herbicide applications) will lead to higher rates of predation of vine pests. A secondary hypothesis that local effects of HMS may be influenced by the surrounding landscape is also investigated.

Sentinel prey baits comprising of *E. postvittana* and *H. zea* eggs were employed on the ground beneath the vines and in the canopy at both the edges and centres of vine blocks with different HMS. Significantly higher predation rates were found at the edge of the vineyard blocks than at the centre, and also where there was between-vine ryegrass growth.

4.2 Introduction

One form of conservation biological control (CBC) is the management of local habitat resources for natural enemies. It can also include ameliorating pesticide impacts on natural enemies through reduced-rate applications (Booth *et al.* 2001) and the use of selective compounds. Agricultural and horticultural crops, including vineyards, involve sometimes-frequent disturbances; tillage, between-row mowing, harvesting and pesticides require arthropods to recolonise crops once displaced by these practices (Kean *et al.* 2003, Gardiner *et al.* 2009). Frequently disturbed crop areas, particularly complete, or in the case of the vines, virtual monocultures, favour the rapid colonisation and growth of pest populations. The resulting ‘natural enemy free space’ (Jeffries *et al.* 1984), can lead to a sudden abundance of pests thereby reducing the likelihood that predators and other natural enemies will keep pests below an economic threshold (Letourneau and Altieri 1999).

In this chapter, the potential to determine the effects of local habitat management strategies (HMS) on predation rates in vineyards is explored. The hypothesis was that low-disturbance habitat management strategies employed in vineyards (not specifically to enhance biological control in most cases), would encourage a higher rate of predation at the vineyard scale. A secondary hypothesis that local effects may work synergistically with landscape effects (Chapter 3) to even further increase predation rates was also examined. Tschamntke *et al.* (2005) discussed the importance of recognising the landscape influence on the local effects on ecological processes, stating that many ‘key’ facilitators of the ecological processes within the system come from outside it, i.e. the surrounding landscape. This often reported generalisation applies to ecosystem services (ES) delivered by mobile organisms e.g. some pest natural enemies and some pollinators. Other ES, including those delivered by the soil, are largely within-field services. ‘Beetle banks’ (Thomas and Marshall 1999) are a good example of the enhancement of within-field ES, predation in that case.

This study was undertaken alongside the investigation in Chapter 3, using the same method of securing sentinel egg baits of *E. postvittana*, and *H. zea* on the ground and in the canopy. Sentinel egg baiting has been used with success to gauge predator

densities and predation rates in a number of studies at the local scale. *H. zea* sentinel egg baits were used in harvested and unharvested lucerne plots (Hossein *et al.* 2002), and also in cotton fields (Diaz *et al.* 2004), and with beet armyworm (*Spodoptera exigua*) in bell-pepper agroecosystems (Bugg and Wilson 1989).

Little is known about *E. postvittana* exposure to predators in vineyards (Frank *et al.* 2007), but these authors postulated that *E. postvittana* larvae on the vineyard floor might encounter a different assemblage of predators relative to that of the canopy, which could differentially affect their survival. Tortricidae larvae exhibit ‘dropping’ behaviour as a defence mechanism when disturbed, and therefore spend time on the ground, increasing the risk of being predated by ground dwelling predators. *E. postvittana* egg masses may therefore also be subject to different predators on the ground than in the canopy. To ascertain if the eggs are taken by both the canopy and ground assemblage of predators in the vineyard is of interest as is whether local HMS has an effect.

The aim of the study in this chapter was to quantify predation rate in egg masses of *E. postvittana* and *H. zea* eggs in vineyards, and to identify local HMS affecting the rate of biological control. Managing *E. postvittana* during the egg stage is optimal as this could be the most effective way of reducing damage by larvae; it is likely most crop damage is caused by late-instar larvae (Dufour *pers. comm.* 2008)

4.3 Methods

This study was run alongside the landscape scale sentinel baiting investigation described in Chapter 3. The experiment ran from January until April 2010 in 25 insecticide-free Waipara valley vineyard blocks in Canterbury, New Zealand (see Chapter 2, Figure 2.3.1 for vineyards used).

The methodology used in Chapter 3 for obtaining, transporting and using sentinel egg baits of *E. postvittana* and *H. zea* were also used in the present study, and is explained in detail in that chapter. Briefly, baits of *E. postvittana* and *H. zea* eggs were placed

in the canopy and on the ground directly below the vine canopy, at the edges and in the centre of vine blocks, retrieved at four days later and the predation rate calculated.

In addition to the work carried out in Chapter 3, in each vineyard block the extent of between- and under-vine row management in terms of disturbance (ploughing, mowing, herbicide use etc.) was recorded, in four different classes; ryegrass, mown ryegrass, mixed sward and bare ground.

4.3.1 Statistical analysis

The number of *H. zea* and proportion of *E. postvittana* eggs predated throughout the sampling period fitted a binomial distribution. Consequently, these data were analysed using a generalised linear mixed model (GLMM) in GenStat. A fixed model was used for the local variables ‘location’, ‘between-vine’ and ‘under-vine’, and vineyard and time were included as random effects in each model to account for any spatial and temporal autocorrelation. The variable ‘location’ describes either effects of non-crop vegetation on predation of eggs at the edge of the vine block, or at the centre of the vine block.

The local effects (location within the vine block, and between- and under- vine vegetation) were also compared as part of a landscape analysis, previously used in Chapters 2 and 3 (see Chapter 2, 2.3 methods). Local effects were compared to uncorrelated landscape effects both as fixed effects (location, between-vine, under-vine, pasture, scrub, shelterbelt, residential vegetation) and vineyard and time were again included as random effects in each model.

Box and whisker plots were used to visually demonstrate differences, with potential outliers indicated as small circles (see figures 4.4.1-5).

4.4 Results

Predation of *H. zea* eggs in both the vine canopy and on the ground was significantly higher at the edge ('location') of vineyard blocks (Table 4.4.1). Figure 4.4.1 shows a trend toward the increasing predation over time, both at the centre and at the edge of blocks ('location'). Figure 4.4.2 demonstrates a trend towards predation of *H. zea* on the ground to be higher than in the canopy.

This difference between predation rate at the centre and at the edge of blocks was also significant when predation of *E. postvittana* eggs on the ground was assessed (Figure 4.4.3). The opposite is true for *E. postvittana* egg predation in the canopy (Figure 4.4.4); however, this may not be a valid result considering the very low predation (almost nil) of *E. postvittana* in the canopy.

E. postvittana ground predation was influenced by the ground cover between the vine rows (Figure 4.4.5). There was a significantly higher predation rate in vine rows with unmown ryegrass compared to mown rye grass and bare ground (Table 4.4.1). There was no synergistic relationship between landscape and local effects on predation rate found in this analysis. There were no significant effects of landscape and local variables interactions; therefore they are not shown in Table 4.4.1. Fixed effects variables are shown individually. Fixed effects landscape variables are included in this analysis as it is assumed that the local effects will not be independent of the landscape.

Table 4.4.1 Generalised linear mixed model (GLMM) analysis for *Helicoverpa zea* and *Epiphyas postvittana*, comparing local effects of non-vine vegetation on predation in vine blocks in 25 vineyards in Waipara valley. **Landscape effects (*in italics*) are included as they likely impact the local effects, but are discussed in Chapter 3.

	Factor	Wald statistic	n.d.f	P-value	Level of significance
<i>Helicoverpa zea</i>					
Canopy baits	Location	24.73	1	<0.001	***
	Between vine	1.09	2	0.589	NS
	Under vine	0.85	1	0.363	NS
	<i>**Pasture</i>	<i>0.02</i>	<i>1</i>	<i>0.898</i>	<i>NS</i>
	<i>**Scrub</i>	<i>2.89</i>	<i>1</i>	<i>0.108</i>	<i>NS</i>
	<i>**Shelterbelt</i>	<i>0.00</i>	<i>1</i>	<i>0.957</i>	<i>NS</i>
	<i>**Residential vegetation</i>	<i>1.38</i>	<i>1</i>	<i>0.256</i>	<i>NS</i>
Ground baits	Location	23.85	1	<0.001	***
	Between vine	2.67	2	0.286	NS
	Under vine	1.04	1	0.321	NS
	<i>Pasture</i>	<i>0.97</i>	<i>1</i>	<i>0.340</i>	<i>NS</i>
	<i>Scrub</i>	<i>0.01</i>	<i>1</i>	<i>0.919</i>	<i>NS</i>
	<i>Shelterbelt</i>	<i>0.07</i>	<i>1</i>	<i>0.793</i>	<i>NS</i>
	<i>Residential vegetation</i>	<i>0.77</i>	<i>1</i>	<i>0.389</i>	<i>NS</i>
<i>Epiphyas postvittana</i>					
Canopy baits	Location	2.28	1	0.135	NS
	Between vine	0.11	2	0.948	NS
	Under vine	0.33	1	0.571	NS
	<i>Pasture</i>	<i>0.58</i>	<i>1</i>	<i>0.456</i>	<i>NS</i>
	<i>Scrub</i>	<i>0.50</i>	<i>1</i>	<i>0.491</i>	<i>NS</i>
	<i>Shelterbelt</i>	<i>1.26</i>	<i>1</i>	<i>0.277</i>	<i>NS</i>
	<i>Residential vegetation</i>	<i>1.37</i>	<i>1</i>	<i>0.258</i>	<i>NS</i>
Ground baits	Location	26.05	1	<0.001	***
	Between vine	11.77	2	0.009	**
	Under vine	1.17	1	0.293	NS
	<i>Pasture</i>	<i>0.98</i>	<i>1</i>	<i>0.335</i>	<i>NS</i>
	<i>Scrub</i>	<i>0.60</i>	<i>1</i>	<i>0.450</i>	<i>NS</i>
	<i>Shelterbelt</i>	<i>0.09</i>	<i>1</i>	<i>0.765</i>	<i>NS</i>
	<i>Residential vegetation</i>	<i>0.16</i>	<i>1</i>	<i>0.691</i>	<i>NS</i>

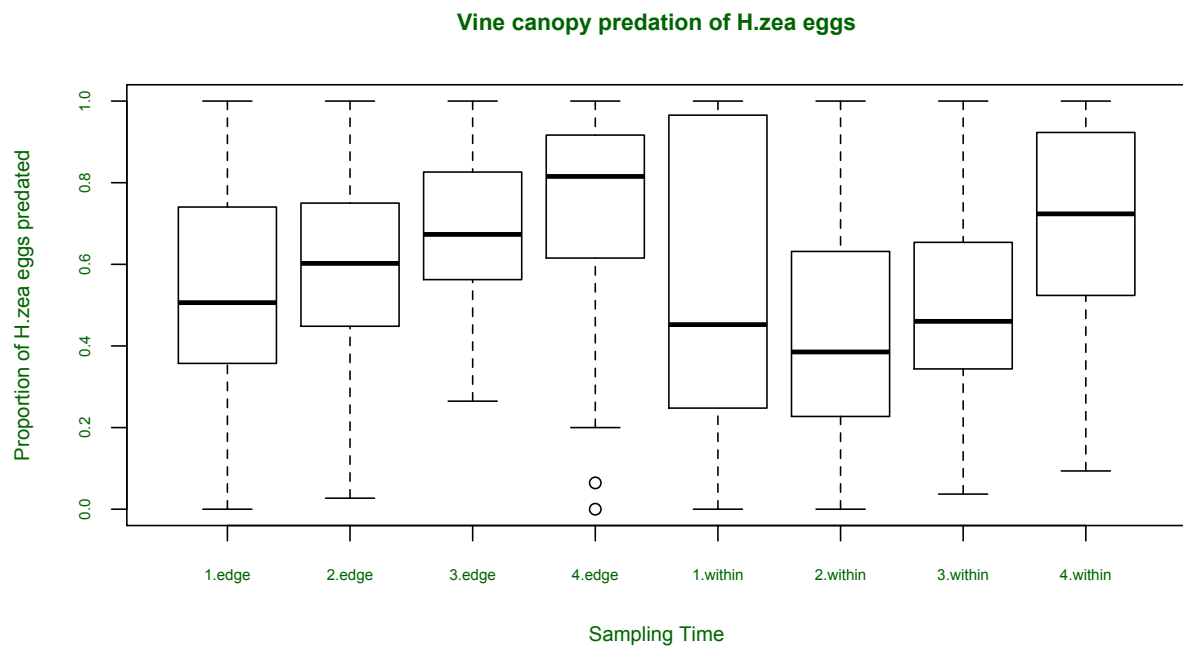


Figure 4.4.1: Comparison of the proportion of *H. zea* eggs predated in the vine canopy at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at four time periods.

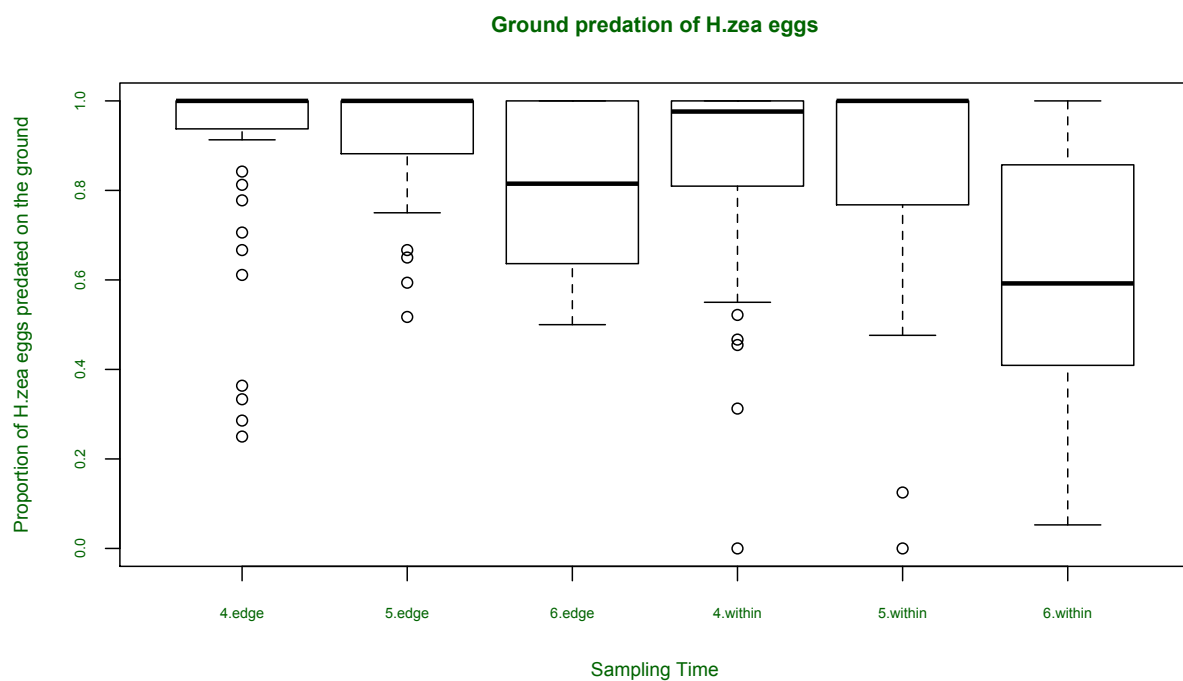


Figure 4.4.2: Comparison of the proportion of *H. zea* eggs predated on the ground at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at three time periods.

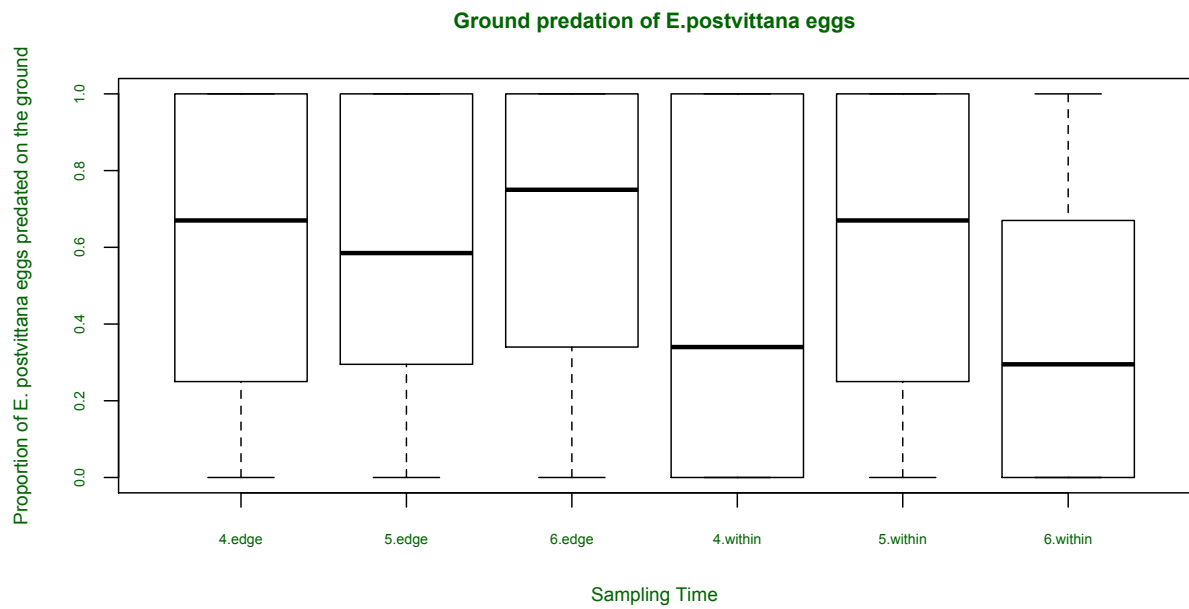


Figure 4.4.3: Comparison of the percentage of *E. postvittana* eggs predated on the ground at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at three time periods (time periods 4, 5 and 6).

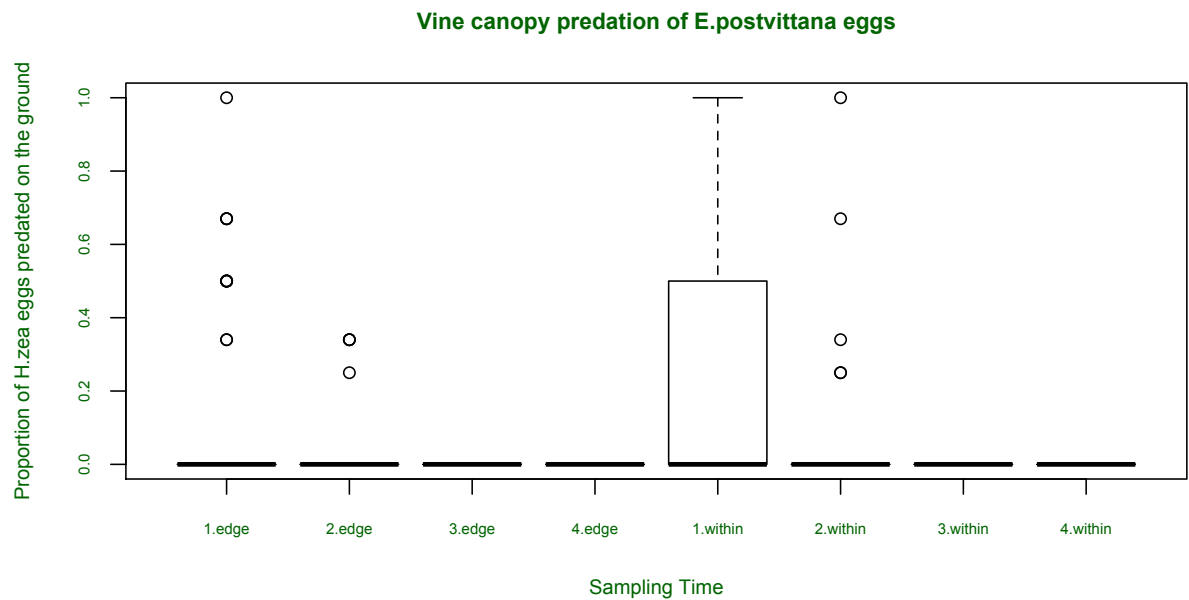


Figure 4.4.4: Comparison of the percentage of *E. postvittana* eggs predated in the vine canopy at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at four time periods.

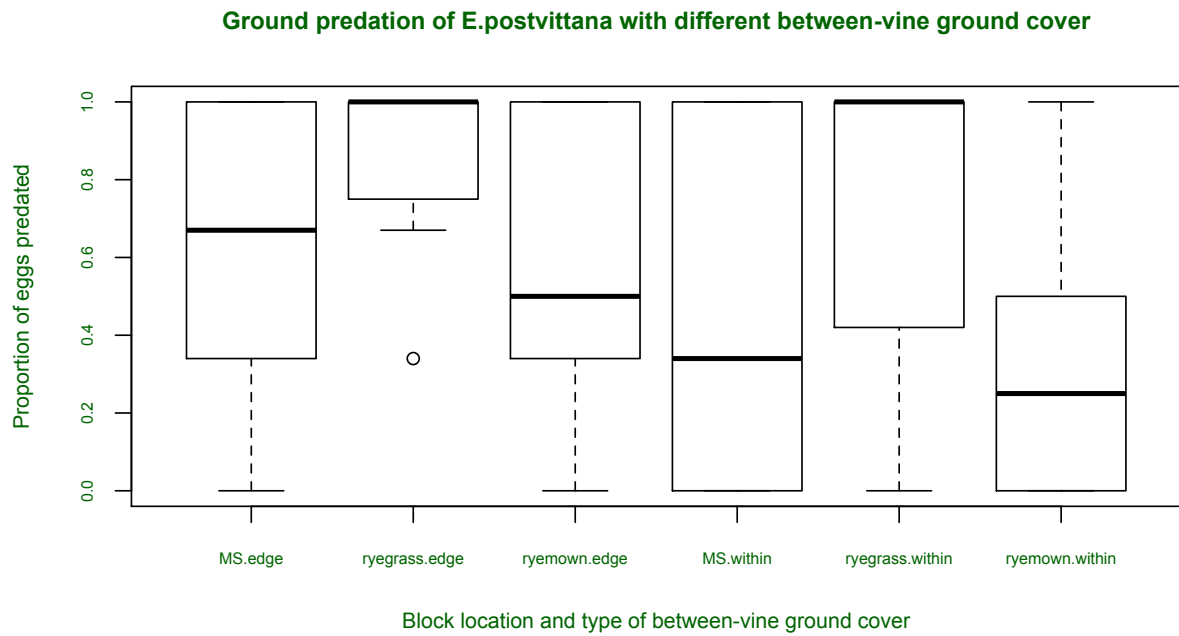


Figure 4.4.5 Comparison of the percentage of *E. postvittana* eggs predated on the ground at the edge of a vineyard block, and within the block, in 25 vineyards, sampled at three time periods, with three different between-vine ground covers; ryegrass (left to grow), ryegrass mown (mown as per normal management) and MS (mixed sward).

4.5 Discussion

4.5.1 Overview

In this chapter, it has been shown that the ability of non-crop vegetation to supply biological control (BC) through predation rate assessments was a function of local habitat management. The predators in this study responded to the location at the edge of vineyard blocks and where ryegrass was left to grow between the vines; areas with lower disturbance.

4.5.2 Local habitat management to enhance biological control: influence on predation rate

Previous authors have illustrated the importance of natural enemies in the suppression of both *E. postvittana* and *H. zea* populations at the field scale (Tilman *et al.* 2001, Pfannenstiel and Yeargan 2002, Diaz *et al.* 2004, Frank *et al.* 2007, Stephens *et al.* 2008, Outward *et al.* 2008, Danne *et al.* 2010, Suckling and Brockerhoff 2010), and other crop pests at the landscape scale (Thies and Tschardtke 1999, Bianchi *et al.* 2005, Gardiner *et al.* 2009). Predator and parasitoid abundance at the landscape scale may increase but that alone may not be enough to effect pest population suppression (Landis and Marino 1999, Holland and Fahrig 2000, Ostman *et al.* 2001, Bianchi *et al.* 2006).

At the field plot scale, Stephens *et al.* (1998) found significantly higher levels of parasitism of *E. postvittana* larvae when buckwheat was planted in apple orchards compared with control areas and also increased numbers of the *E. postvittana* parasitoid wasp *D. tasmanica* captured above the buckwheat. Sentinel baiting with *E. postvittana* eggs at the vineyard scale was also (as well as this study) employed by Danne *et al.* (2010) who found that Australian native cover crops had a higher abundance of predators and predation than did the control cover crops. Studies of *H. zea* in cotton crops have revealed nearby non-crop vegetation to increase *H. zea* populations in crops (Outward *et al.* 2008, Jackson *et al.* 2008), but also increase the abundance of predaceous arthropods (Outward *et al.* 2008), which Tillman *et al.* (2004) found controlled numbers of heliothines (including *H. zea*) to below economic threshold levels.

Because of the potential for *E. postvittana* caterpillar damage to young grapes (Suckling and Brockerhoff 2001), predation as early as possible in their lifecycle (i.e. the egg stage) is key in preventing the caterpillars reaching ‘economic threshold’ levels. In one of the vineyards in this study, the ‘economic threshold’ was if more than 0.5% of bunches of grapes were infested with one or more larvae (J-L Dufour *pers. comm.* 2008).

In this study, the effect of standard (‘conventional’) habitat management of 25 different vineyards on predation rates was investigated. Using sentinel baiting, it was shown that predators were more effective at the edges of vineyard blocks than in the centre, and that ryegrass left to grow between the vine rows also supported a higher predation rate. The edges of the vine blocks were relatively undisturbed compared with the vine inter-rows that were managed, either with herbicide, mowing or tillage and supported greater biological control of *E. postvittana* and *H. zea* eggs by predators.

Such an increase in predation near the crop edges, in this case vine block edges, compared with the crop interior is common in many studies (Baggen and Gurr 1998, Thies and Tschardt 1999, Nicholls *et al.* 2001, Tylianakis *et al.* 2004) and often attributed to the proximity of important alternative resources in these undisturbed habitats, such as shelter and alternative host/prey species (Landis *et al.* 2000, Tylianakis *et al.* 2004). Landis *et al.* (2000) suggested that since many agro-ecological studies highlight the importance of natural habitats as a source of natural enemies, including how far away these supporting resource areas are from crops, proximity of crops to habitat edges may be similarly key in encouraging predator abundance and impact. For example, Tschardt *et al.* (2002) found that parasitism rate of rape pollen beetles exhibited a distinct edge effect, with increased parasitism near the crop field edge, although only in simple landscapes; where there was more complexity in the landscape the edge effects disappeared. Halaj *et al.* (2000) suggest that associations between non-crop vegetation ‘cover’ and predator abundance indicate that weeds may act as a natural refuge, promoting early-season colonisation into the crop and increasing predation. To promote biological control in agricultural systems such as vineyards, it may be desirable to maintain some year-round

undisturbed habitat directly adjacent to vine-block edges to favour these predatory natural enemies in the crop. Key questions remain; however, and may be specific to particular crop/pest/natural enemy associations. These questions include what type of habitat, where and when it should be deployed and its effects, if any, on the pest insects themselves. Also, 're-engineering' farm landscapes that have lost plant and other biodiversity has high social and economic impediments associated with it (Cullen *et al.* 2008).

Another factor that may have contributed to a higher predation rate at the edges of the vine blocks is disturbance. The intensely managed environment of many agro-ecosystems can be unfavourable for natural enemies; agricultural practices, both chemical (pesticides, herbicides) and mechanical (tilling, mowing, ploughing), can reduce natural enemy populations in crops (Landis *et al.* 2000, Menalled *et al.* 2001). The vineyards in this study employed habitat management strategies ranging from very intense herbicide (used below the vines), and mowing (between the vine rows) or tilling regimes, to relatively low-disturbance, such as intermittent mowing and/or hand weeding. However, all were similar in that the edges of the vine blocks were essentially left alone. This may create a more stable environment for ground dwelling predators in particular, such as spiders, mites, harvestmen and earwigs; all of these are predators of *E. postvittana* (Frank *et al.* 2007). Tschardtke *et al.* (2005) discussed the possible effects of agricultural intensification on the disruption of ecosystem services including biological control, with the hypothesis that simple landscapes may not supply the resources needed by natural enemies and their abundance may be lower in these environments. Populations of natural enemies can be reduced by activities within the crop and their persistence may depend on reinvasion, which in turn can depend on locally available populations from relatively undisturbed vegetation (Kruess and Tschardtke 1994, Zabel and Tschardtke 1998, Golden and Crist 1999). There is little information on the impact of disturbance on invertebrate communities and pest control in vineyards, apart from some data on tillage (Sharley *et al.* 2008). In the present study, it was found that predation was higher at the edges of vineyard blocks, where the vegetation was left to grow, than in the interior, and was also higher in unmown ryegrass areas between vine rows. These areas in this study had fewer disturbances by mechanical or chemical inputs and supported a greater predation rate of sentinel egg baits of *E. postvittana* and *H. zea* than the vineyard block interior.

Thies and Tscharrntke (1999) found 50% higher parasitism at the edges of oilseed rape and this reduced to 20% where there was no field margin. However, while they found the type of field margin did not affect the rate of parasitism, older, undisturbed field margins enabled natural enemy populations to build up and enhance dispersal into the crop fields.

4.5.3 The predator response

The natural enemies responsible for the predation in the present study may have responded to local effects of non-crop vegetation because their dispersal is at a small spatial scale. Thomson and Hoffman (2010) found that predation of *E. postvittana* increased significantly in Australian vineyard areas only 50m away from adjacent non-crop vegetation, indicating predators' use of local resources having a positive impact. Neither Thomson and Hoffman (2010) nor the work in this chapter identified which predators were influenced at this local scale; however, Thomson and Hoffman (2010) proposed that coccinellids could be responsible, or perhaps other known predators; ants (Hymenoptera: Formicidae) and earwigs (Dermaptera). Frank *et al.* (2007) found, using video techniques, that Formicidae (ants), Forficulidae (earwigs) and Opiliones (harvestmen) to be the most voracious predators of *E. postvittana* larvae in a New Zealand vineyard. The work in Chapter 5 also used video monitoring, finding that Opiliones and Forficulidae species were the main predators in the vineyard block.

4.5.4 Conclusions

This work in this chapter demonstrates that biological control services provided by generalist predators in North Canterbury wine country are dependent largely on their immediate environment; shelter and resources available at the vineyard scale.

As simple agricultural landscapes tend toward monocultural dominance and therefore higher intensity inputs, the results of this study suggest that it may be the consequent disturbance that negatively impacts largely the natural enemies that forage at smaller spatial scales. Provision of undisturbed habitat within or adjacent to the vineyard could be helpful in increasing predation of eggs of *E. postvittana* and *H. zea* in these

crops. However, since natural enemies respond to non-crop vegetation at different spatial scales, dependent on their particular dispersal; it would be helpful to know what predators are in this area to be able to provide resources to them and influence a higher rate of predation of vineyard pest eggs. To this end, within vineyard habitat manipulation coupled with video quantification of predation were carried out in Chapter 5.

Chapter 5:

Video analysis of predation rate of two species of lepidopteran ‘sentinel’ prey eggs in relation to inter-row vegetation.

5.1 Abstract

Local non-crop vegetation can provide shelter and resources such as alternative prey and nectar to predators. This is particularly important when disturbance through crop management, such as grass mowing or using herbicide, may cause a reduction in predator populations. Therefore it is vital to understand what natural enemies are active in an agricultural system in order to provide appropriate resources as part of a habitat management strategy. In this chapter, the aim was to obtain information on which predators occur and how they behave when encountering prey. Sentinel egg baits and infrared video monitoring were used to answer these two questions. The objective of the work in this chapter was therefore to determine the identity, predation rate and feeding behaviour of the ground-foraging predators in a vine block.

Hypotheses tested:

- That predator abundance and predation rate are higher in mixed weedy inter-row sward and ryegrass (control) strips than in herbicide-treated bare ground strips.
- That the edge of the vine block will support higher predation rates than in the centre in both herbicide treated and control strips.

Harvestmen and earwigs were the main predators of sentinel egg baits and were more prevalent in areas of the vine block with non-crop vegetation, such as the edge of the block, and in the control (no herbicide) strips. The rate of predation was higher at the edge than the centre as hypothesised and it was also higher in control strips than in herbicide treated areas.

5.2 Introduction

The work in Chapters 2 and 3 showed a single effect of vegetation at the landscape scale on Waipara vineyard pest abundance, and no effect at all on predation of sentinel egg baits of *E. postvittana* or *H. zea*. However, at the field scale, in Chapter 4, it was shown that predators were more effective at the edges of vineyard blocks than in the centre. Weedy ryegrass between the vine rows also supported a higher predation rate (see Chapter 4). Therefore the study in this chapter focussed on experiments that manipulated the local, within vineyard non-crop vegetation and its effects on predation rate.

The effect of non-crop vegetation and local habitat management methods on predators has been demonstrated at the field scale for many systems (Altieri and Whitcomb 1980, Mensah 1999, Nicholls *et al.* 2000, Hossain *et al.* 2000, Halaj *et al.* 2000, Landis *et al.* 2000, Hossain *et al.* 2002, Frank and Shrewsbury 2004). Local non-crop vegetation can provide shelter and resources such as alternative prey and nectar to predators. Mensah (1999) found higher densities of predatory beetles (Coleoptera), bugs (Hemiptera), lacewings (Neuroptera) and spiders (Araneida) in planted lucerne (*M. sativa*) strips in cotton fields, and importantly, more than twice the predation rate in the crop itself. In vineyards in California, Nicholls *et al.* (2000) found that planting of buckwheat (*F. esculentum*) and sunflower (*Helianthus annuus* L.) between rows of vines yielded higher numbers of predatory insects including spiders, and lower densities of pest species.

Altieri and Whitcomb (1980) found an increased abundance of predators near weedy areas, which could be attributed to a lack of disturbance, thereby providing shelter. Disturbance through crop management may cause a reduction in predator populations directly by increasing emigration or mortality (Lee, Menalled and Landis 2001, Thorbek and Bilde 2004), and indirectly through disruption of their habitat (Hossain *et al.* 2002, Thorbek and Bilde 2004). Chemical disturbance such as herbicide use may also reduce arthropod predator populations. For example, vineyards often apply broad-spectrum herbicides directly beneath the vines to avoid competition by weeds (Dufour *pers. comm.* 2008, Cullen *et al.* 2010). This practice may also remove habitat for natural enemies. Mechanical disturbances such as soil cultivation and grass

cutting can also cause disruptions in natural enemy populations from which they need to recover (Hossain *et al.* 2002). This disturbance may be frequent in each growing season. Thorbek and Bilde (2004) found grass cutting significantly reduced spider populations where the cut grass was removed, but there was an increase in populations where the cut grass was left to dry. Conversely, Minarro and Dapena (2003) found carabid beetles (Coleoptera: Carabidae) in higher densities in the tilled and herbicide plots than in plots with straw mulches or pine bark. This marked difference in behaviour emphasizes the importance of understanding the natural enemy in order to provide the resources and improve efficacy as part of a habitat management strategy. (Wratten *et al.* 2003, Pfannenstiel and Yeargan 2002, Frank *et al.* 2007). Understanding individual species, rather than just guilds of predators, is likely to be of importance in increasing predatory efficacy. Losey and Denno (1998) found that two species (in different but phenologically overlapping guilds) have a synergistic relationship. Foliar-foraging *Coccinella septempunctata* L. (Coleoptera: Coccinellidae) and ground-foraging *Harpalus pennsylvanicus* (Coleoptera: Elateridae) working together almost doubled the sum of their individual predation rates. Their prey, the pea aphid (*Acyrtosiphon pisum* (Hemiptera: Aphididae)), has a 'dropping' behaviour elicited by *C. septempunctata*, that makes aphids more susceptible to predation by *H. pennsylvanicus* (Losey and Denno 1998). Landis *et al.* (2000) found that structural diversity in the landscape may facilitate certain Carabidae species' movement within an agricultural system; however, for other species' of this family it may obstruct it. Clearly, a thorough understanding of individual species can be vitally important in employing habitat management strategies. However, it can be difficult to know which predators are present and affected by non-crop vegetation and habitat management strategies that growers may employ (Pfannenstiel and Yeargan 2002, Frank *et al.* 2007) and whether careful management of the resources can enhance efficiency of these predators (Frank and Shrewsbury 2004). A number of approaches have been used to determine the identity of predators' prey; gut dissection (Sunderland and Vickerman 1980), enzyme-linked immunosorbant assay (ELISA) (Sopp *et al.* 1992) and visual observation (Pfannenstiel and Yeargan 2002). These techniques have disadvantages such as difficulties in identifying pest species eaten, can be expensive and also time consuming (Merfield *et al.* 2003). More recently, polymerase chain reaction (PCR) methods have been used. PCR is a technique used in many applications in molecular biology to amplify a specific region of a DNA

strand, in this case, to identify the DNA of a prey species in a predator's gut. This technique has largely displaced the protein based approach (e.g. ELISA) as the primer sequences necessary for replication are available to anyone, and the antibodies used for ELISA, for example, are very expensive to purchase and very difficult to manufacture. However, even though a primer may already exist for a particular prey species' DNA, it may need further testing in the specific environment being studied. While the PCR method can provide qualitative results, there are factors that are not taken into account such as secondary predation, scavenging and predation occurring during sampling (Symondson. in press), which may give inaccurate data.

Frank *et al.* (2007) and Merfield *et al.* (2003) both had success using time-lapse video not only for identifying predators but also monitoring behaviour. Information on diurnal variations in activity and predation rate between predators (Merfield *et al.* 2003) and how predators behave when encountering prey (Frank *et al.* 2007) were attainable using video. Araj *et al.* (2011) also had success using video to study the behaviour of the pea aphid parasitoid *Aphidius ervi* (Haliday) (Hymenoptera: Ichneumonidae) and its hyperparasitoid *Dendrocerus aphidum* (Rondani) (Hymenoptera: Megaspilidae).

The objective of this chapter was therefore to determine the identity, predation rate and feeding behaviour (time spent and visits to the sentinel egg baits) of the ground assemblage of predators in a vine block. Infrared video monitoring was used to test the hypothesis that predator abundance and predation rate would be greater in mixed weedy sward and ryegrass (hereafter referred to as 'ryegrass (control)') strips than in herbicide treated bare ground strips. A comparison of edge effects of the vine block to the centre was repeated (see Chapter 4). However, each night the sentinel bait was in a different location i.e., a different ground treatment site, herbicide or ryegrass (control). The hypothesis was that the edge of the vine block supports greater predation rates than in the centre in both herbicide treated strips and ryegrass (control) strips.

5.3 Methods

The potential impact of bare ground and disturbance on arthropod predators and predation of *E. postvittana* and *H. zea* at the vineyard scale was tested. The study was carried out from February 16 to March 17 2010 in a vine block where no insecticide had been used at Mud House Wines' vineyard in Waipara, Canterbury, New Zealand.

The experiment was set up in a 20 bay vine-block with 10 replicates of a herbicide treatment (Buster®, Kiwicare) (glufosinate-ammonium) randomly assigned to vine bays. Vine bays were a standard 5m length with 5 vines per bay. The viticulturist at Mud House Wines, Jean-luc Dufour, applied this herbicide at 1:10 concentration 10 days before the experiment began to ensure full efficacy. The other 10 vine bays were used as the controls, under 'normal' management (mixed weedy sward and ryegrass mown to approximately 6cm high) and were not mown during the experiment time. Herbicide-treated bays were mown to ground level and any surplus dead vegetation removed, resulting in bare ground.

Sentinel egg baits of *E. postvittana* and *H. zea* were used on the ground directly beneath the vines, using the same methodology as in Chapter 3 (see Figure 3.3.2). Data from these baits were collected in the same manner as Chapter 3 also.

An infrared (IR) camera (Sanyo CVCC-HD4600 Full HD 1080p Day/Night Network Camera, with accompanying 12 element IR illuminator), was placed in one vine bay in each of a herbicide treatment and control. A different bay was used each night, for each treatment, randomly assigned out of the 10 of each available. Edge effects, compared to vine-block centre, on predation and predators were also assessed in this experiment. The camera was randomly assigned to be at the edge or the centre of the vine-block (Table 5.3.1) once treatment randomization had taken place; the second camera was assigned the other treatment (Figure 5.3.1).

Table 5.3.1 Randomisation of herbicide, control, edge and centre assignments to each camera. =herbicide, = control, ‘E’ = edge, ‘Ce’ = centre. Each night, the cameras were in a different randomly assigned treatment area.

Nights	1	2	3	4	5	6	7	8	9	10
Camera 1	E	E	Ce	E	Ce	E	E	E	Ce	E
Camera 2	Ce	Ce	E	Ce	E	Ce	Ce	Ce	E	Ce

The cameras were placed approximately 25cm over sentinel egg baits, with the lens zoomed and focussed so that the bait papers and immediate surrounding area would be monitored, and set to record from 20-00h to 06-00h whenever the IR sensor detected movement. The cameras monitored an area approximately 20cm in diameter, encompassing the entire sentinel bait card set-up (with both egg types) and immediate surrounds (approx. 2cm around bait papers). This provided two measurements of predator activity: (1) the number of times a predator visited the sentinel baits, and (2) the duration of each visit. When two predators were present, each species’ duration of time spent on the bait was recorded separately, and any associated behaviour was noted.

Each ‘camera night’ was downloaded the next day using a video download software for this purpose (HDC Downloader). Each video was watched and activity was noted for analysis in consecutive five-minute recordings. These were not consecutive in real time because the movement sensor determined recording periods, as explained above.

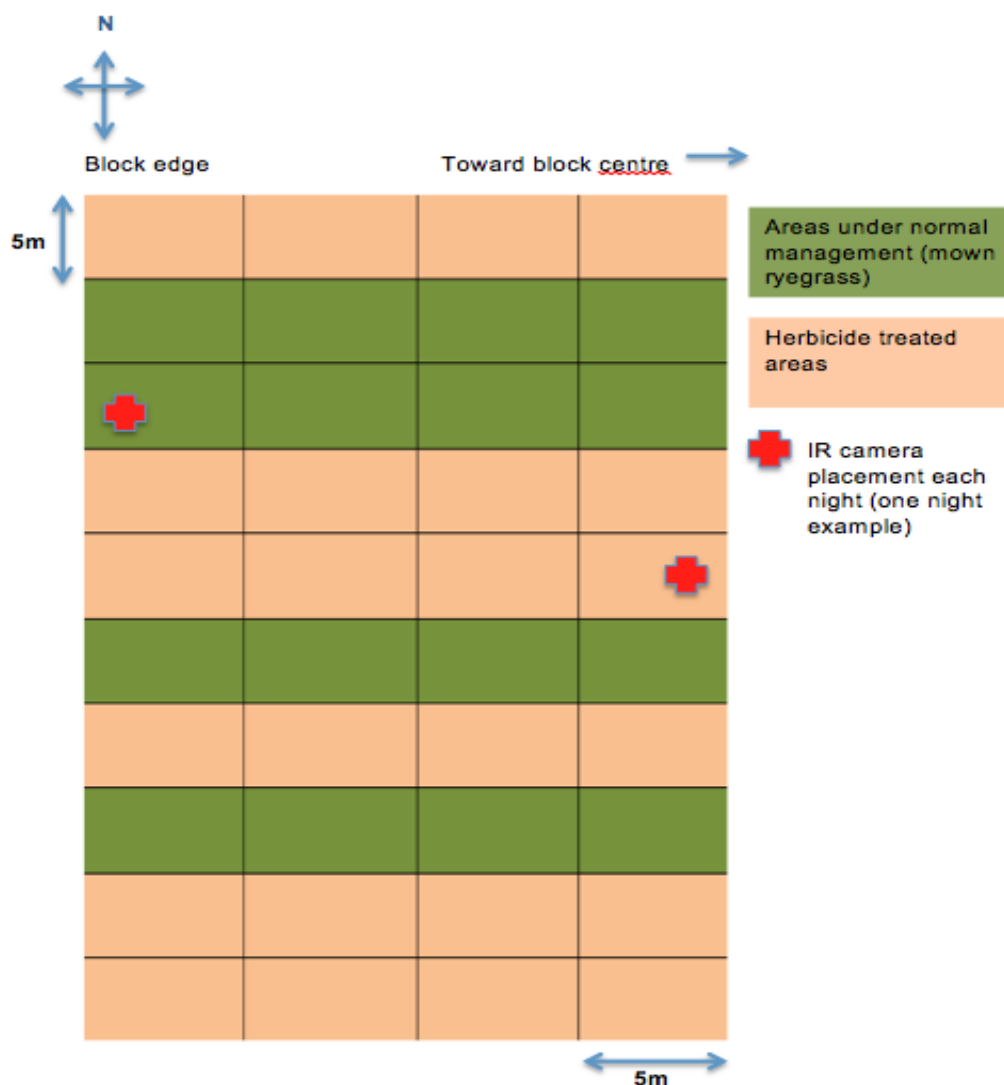


Figure 5.3.1 IR camera placement and experiment design (example) in a vine block at Mud House Wines, Waipara.

5.3.2 Statistical analysis

The data collected for the percentage of time spent on baits by predators was assessed using a repeated measures REML analysis as both fixed and random effects were needed in the model and the data were normally distributed. Temporal autocorrelation was avoided by introducing the combination of variables ‘location’ and ‘treatment’ as a new variable and the interaction of this variable with time was included as a random effect.

The number of *H. zea* and proportion of *E. postvittana* eggs predated throughout the sampling period fitted a binomial distribution. Consequently, these data were analysed using a generalised linear mixed model (GLMM) with a logit link function. This analysis was calculated in ‘R’ with the package ‘glmm’.

5.4 Results

The predators identified were harvestmen (*P. opilio*) and the European earwig (*F. auricularia*). Both species spent significantly more time ($P < 0.01$) at sentinel egg baits in the ryegrass (control) strips than in the herbicide treated strips. Similarly, these predators also spent significantly more time ($P < 0.02$) at sentinel egg baits at the edge of the vine block, regardless of treatment, than at baits in the centre. For all treatments, the time harvestmen remained at the baits was significantly longer ($P < 0.001$) than that for earwigs (Table 5.4.1, Figure 5.4.1).

Harvestmen visited sentinel egg baits in ryegrass (control) strips 54.8% more often than did earwigs. Harvestmen and earwig visits largely occurred between 22-00h and 01-00h, although two visits by harvestmen were recorded on one of the nights at 04-00h (Figure 5.4.2). There were fewer visits to sentinel baits by harvestmen in herbicide treated strips than in ryegrass (control) strips. In a similar trend, there were 27.2% fewer visits by earwigs in herbicide treated strips than in ryegrass (control) strips. Visits by both harvestmen and earwigs occurred between 23-00h and 01-00h (Figure 5.4.3).

Harvestmen visited sentinel egg baits at the edge of the vine block 80% more often than did earwigs, but were equally frequent at the centre of the vine block. There were 83% fewer visits to sentinel baits by harvestmen and 45% fewer visits by earwigs in the centre of the vine block compared with the edge (Figures 5.4.4, 5.4.5).

The predation rate of *H. zea* eggs at the edge of the vine block was significantly higher ($P < 0.001$) than at the centre. However, there was no such effect on the predation rate of *E. postvittana*. Predation of *H. zea* was also significantly higher ($P < 0.01$) in ryegrass (control) strips than in herbicide treated strips. The predation rate of *E. postvittana* did not differ between the ryegrass (control) strip and the herbicide treated strips (Table 5.4.3).

Table 5.4.1 A repeated measures REML for length of time of predator presence on baits. Treatment = the effect of herbicide areas, Location = the effect of position (edge or centre), Species = H or E.

	Factor	Wald statistic	n.d.f	P-value	Level of significance
Single effects	Treatment	12.96	1	0.002	**
	Location	6.37	1	0.020	*
	Species	30.82	1	<0.001	***
Interaction effects	Treatment x Location	0.18	1	0.672	NS

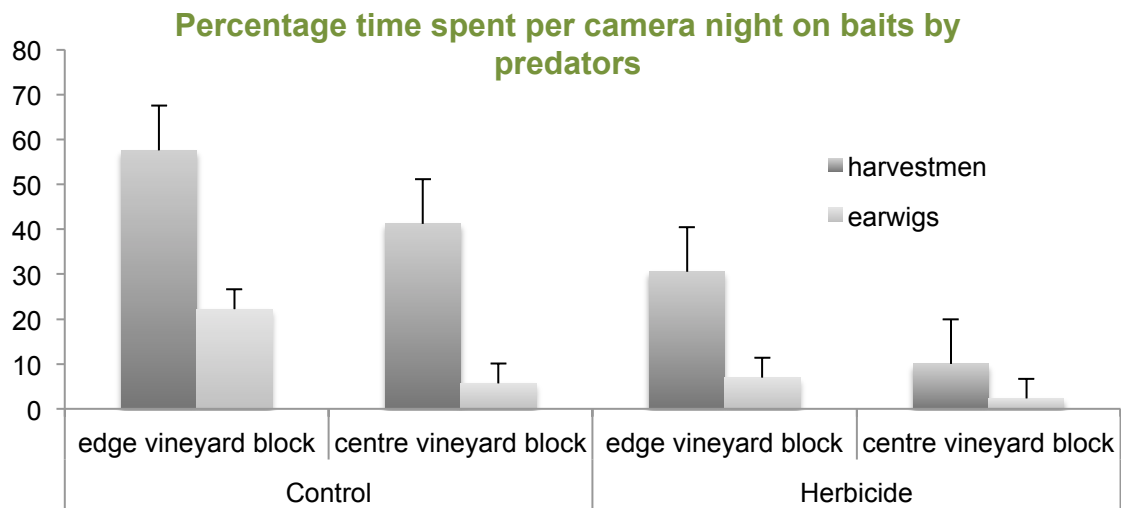


Figure 5.4.1

Comparison of the percentage of time/camera night spent on baits by two predator species in herbicide treated areas vs. control areas, in two locations: the edge of the vineyard block, and centre of the vineyard block (see Figure 5.3.1).

Table 5.4.2 Total time (h:min:s) spent on sentinel egg baits by each predator species in each treatment (see Table 4.4.1)

	Ryegrass, edge	Ryegrass, centre
Harvestmen	1:15:24	0:54:12
Earwigs	0:29:31	0:07:40
	Herbicide, edge	Herbicide, centre
Harvestmen	0:40:26	0:17:16
Earwigs	0:09:11	0:04:10

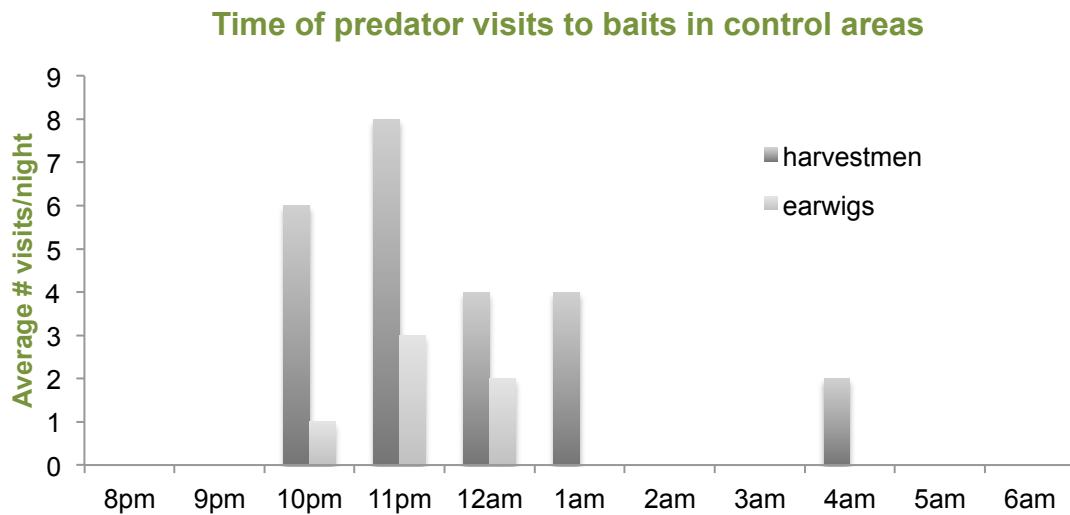


Figure 5.4.2 Average number of visits by predators each night in control areas

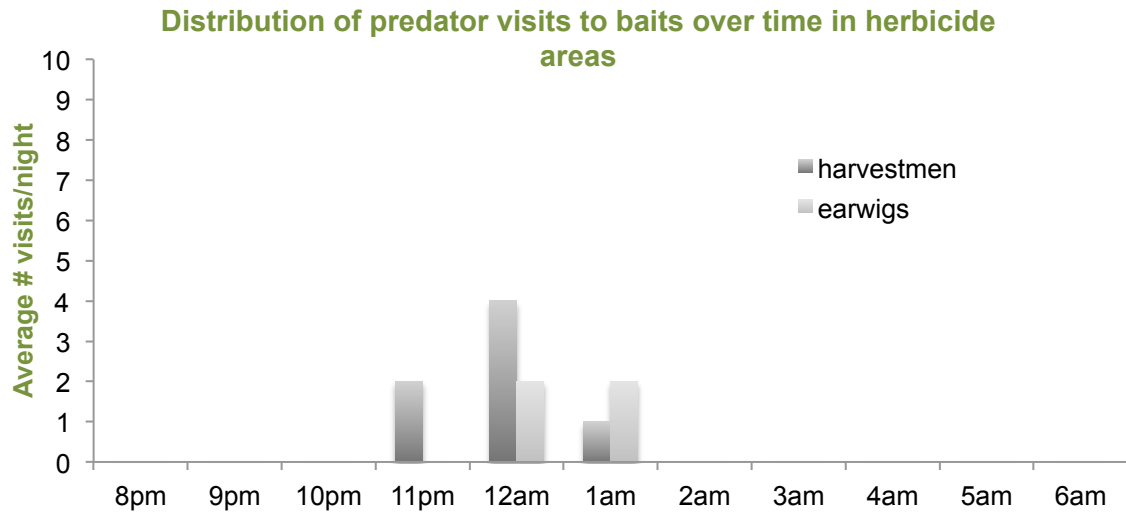


Figure 5.4.3 Average number of visits by predators per night in herbicide areas

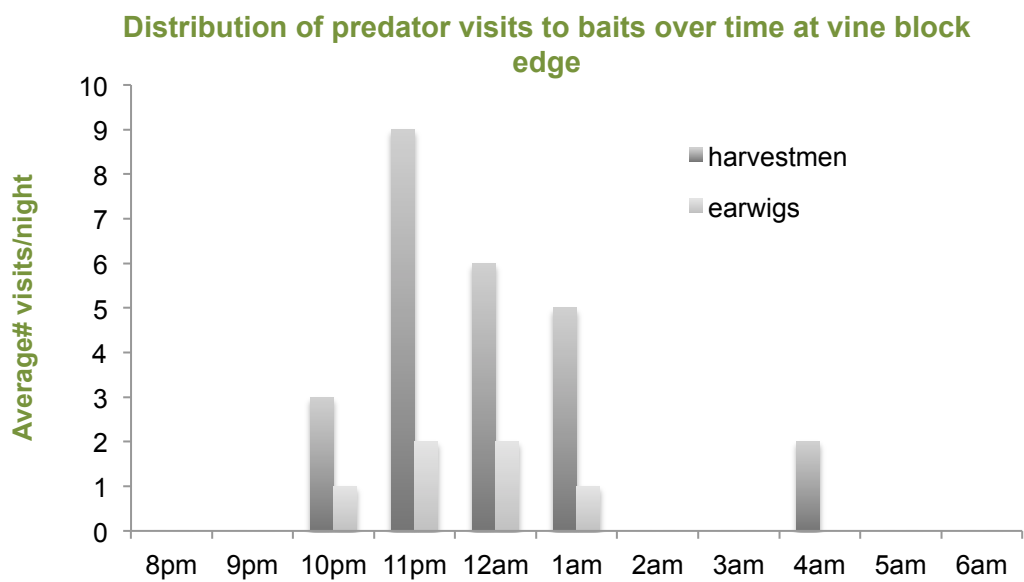


Figure 5.4.4 Average number of visits by predators to baits at the edge of the vine block, regardless of treatment

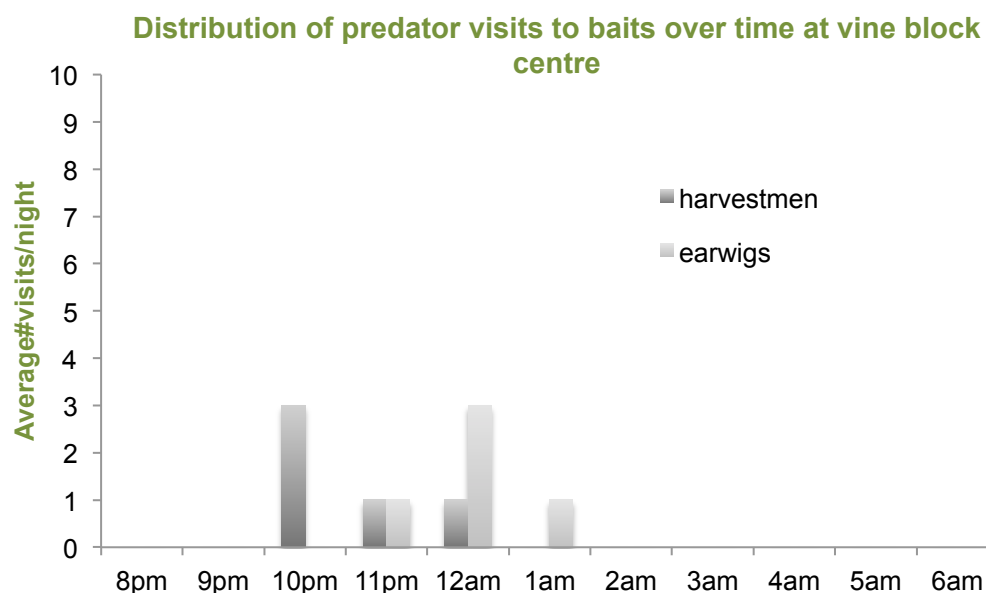


Figure 5.4.5 Average number of visits by predators to baits in the centre of the vine block, regardless of treatment

Table 5.4.3 Generalised linear mixed model (GLMM) analysis for *H. zea* and *E. postvittana* predation rate of ground baits in a vine block at Mud House winery in Waipara valley. Location = the effect of position in the vine block (edge or centre). Treatment = the effect of the vegetation present (herbicide treated or control).

Factor	Change in AIC	n.d.f	P-value	Level of significance
<i>Helicoverpa zea</i>				
Random effects only model				
Location	23.5	1	<0.001	***
Treatment	16.28	1	0.009	**
Location*Treatment	27.01	1	0.542	NS
<i>Epiphyas postvittana</i>				
Random effects only model				
Location	73.36	1	0.112	NS
Treatment	74.49	1	0.263	NS
Location*Treatment	74.97	1	0.171	NS

5.5 Discussion

5.5.1 Overview

In this chapter, it has been shown that harvestmen and earwigs were the main predators of sentinel egg baits and were more active in areas of the vine block with non-crop vegetation, such as the edge of the block, and in the ryegrass (control) strips. The rate of predation was higher at the edge rather than the centre as expected, and in ryegrass (control) strips compared to herbicide strips; however, only for *H. zea* egg baits; there was no effect on the predation rate of *E. postvittana* egg baits.

5.5.2 Lack of predatory arthropod diversity

The study vine block had very low diversity of predatory arthropods, based on video data; the two species seen on the video recordings were harvestmen (*P. opilio*) and earwigs (*F. auricularia*). Both of these predators have long been known as beneficial arthropods useful in biological control in many agricultural systems including vineyards (Halaj *et al.* 2000, Schmaedick and Shelton 2000, Vink *et al.* 2004, Merfield *et al.* 2004, Frank *et al.* 2007, Danne *et al.* 2010). Frank *et al.* (2007) used video monitoring of sentinel larvae baits of *E. postvittana* in a New Zealand vineyard and found (as well as Opilionidae and Forficulidae), Formicidae, Hemerobiidae, Chilopoda, Coccinellidae, Staphylinidae, Carabidae and Acari. A study in Australian vineyards using sentinel egg baits of *E. postvittana* to measure predation rate (Danne *et al.* 2010) had an almost completely different assemblage of predators, although Dermaptera species, *F. auricularia* and a native earwig, *Labidura truncata* Kirby (Dermaptera: Labiduridae) were present. Frank *et al.* (2007) used a vineyard with more non-vine vegetation than Danne *et al.* (2010) described, which in contrast was mostly bare ground maintained with herbicide. As well as being in different countries with many associated differences, this habitat difference may also have been why the two studies found different predators on the ground in the same system.

Sentinel egg baiting with *H. zea* to assess predation has also been used in soybean (*Glycine max* L.) and sweet corn (*Zea mays* L.). Pfannenstiel and Yeargan (2002) found that the key predators were different in each crop; Nabidae and Coccinellidae were the dominant predators, in soybean and corn, respectively. Dermaptera and

Opiliones species were present, but they were considered part of a larger assemblage of ‘secondary’ predators. These are considered to be predators that do not target *H. zea* but may predate them if the opportunity arises. However, while it is probable that each agricultural system has a different array of predatory species, it is unlikely that there were only harvestmen and earwigs in the vine block used in this study. Intraguild competition and behaviour may be one explanation; in this study harvestmen were observed fighting with, and chasing off earwigs if the latter tried to feed on the same sentinel egg bait. Possibly other predatory species stayed away when harvestmen were present, and if very small, for example Acari species, they may not have triggered the infrared sensor on the video camera when harvestmen were not at the baits (Merfield *et al.* 2004).

5.5.3 Location and treatment effects on predators and predation rate

Harvestmen and earwigs both spent significantly more time on sentinel egg baits at the edge of the vine block versus the centre. The predation rate of *H. zea* reflects this activity; that of sentinel egg baits at the edge was significantly higher than at the centre of the vine block. This further supports the data shown in Chapter 4 where edge effect of the vine block also increased the predation rate of *H. zea* and *E. postvittana* sentinel egg baits significantly, though in that case, without video data to identify predators. Unfortunately the same effect on predation rate could not be repeated for *E. postvittana* egg baits.

Both harvestmen and earwigs visits to the sentinel egg baits were largely between 22-00h and 01-00h in both the ryegrass (control) strips and the herbicide treated strips. Visits by harvestmen to baits in the herbicide treated strips were less than half (45.2%) the visits made to baits in the ryegrass (control) strips. Similarly, earwigs visited baits in herbicide treated strips almost a third (27%) less than in ryegrass (control) strips. There was significantly more time spent in the ryegrass (control) strip sentinel egg baits by both harvestmen and earwigs. This may have caused the increase in the predation rate of *H. zea* eggs in the ryegrass (control) strips compared to the herbicide treated strips; however, the rate of *E. postvittana* egg predation was not affected. It is important to note that very little of the *E. postvittana* egg baits were consumed at all, therefore time available for predation and egg bait preference may

have been factors. Predation was measured overnight, rather than every four nights as it was in Chapters 3 and 4, and may not have been long enough to reflect a higher predation rate in *E. postvittana* eggs. Combined with this factor, predators may have had a preference for *H. zea* eggs, therefore an effect on predation of *E. postvittana* eggs may have been apparent only after all *H. zea* eggs had been consumed. It is also possible that the ryegrass (control) strips (and edge vegetation) supported alternative prey for *P. opilio* and *F. auricularia*, and they may have had the luxury of choosing only ‘easy prey’ - the single and large *H. zea* eggs, rather than the flat and waxy *E. postvittana* egg masses.

Another or additional hypothesis is that the majority of predators may have left for adjacent vine or pasture habitats when the study site was mown. Hossain *et al.* (2002) found that predation rates of *Helicoverpa* species’ sentinel egg baits were highest near unharvested plots of lucerne that were closest to the most recently harvested ones where predator densities had previously been greatest. Therefore there may not have been the volume of predators needed to effect the predation rate of *E. postvittana* in the short time available. This ‘exodus’ might also explain why there was a strong edge effect on predation rate, as more predators may have used these refuges directly after the study strips were mown. It may also have contributed to the lack of predator diversity found in this study, as few predators may have remained in the vine block. There was more activity by predators visiting sentinel egg baits at the edge of the vine block rather than the centre, with 83% more visits by harvestmen and 45% more visits by earwigs.

5.5.4 Differences between predator species behaviour

For all treatments, harvestmen stayed at the sentinel egg baits significantly longer than did earwigs. Frank *et al.* (2007) found harvestmen and earwigs to be active on the ground for slightly more than 3h (3:09:00) and 2.75h (2:47:46), respectively, across five nights in a vineyard at Lincoln University, Canterbury, New Zealand. The earwigs in the present study were on sentinel egg baits for less than an hour (0:50:32) in total, while harvestmen were on sentinel egg baits for almost the same length of time as Frank *et al.* (2007) recorded; approximately three hours (3:07:18). Harvestmen are unique among arachnids as they do not have a sucking stomach and a

filtering mechanism but have mandibulate mouthparts and ingest tiny particles of food (Schmaedick, unpublished) therefore they may take more time to consume a prey item. Earwigs move much more quickly to take eggs from the baits and are known to be voracious predators (Frank *et al.* 2007). This may explain why harvestmen were on the baits for longer time periods. Frank *et al.* (2007) found there were fewer earwigs spending less time on baits on the ground because they are more efficient predators in the vine canopy; they were recorded predating *E. postvittana* larvae in the canopy for almost 10 times as long (20:00:00).

Predation in the canopy - the leaves and grape bunches - was not measured in the present study. In Chapter 4 it was found that predation of *H. zea* sentinel egg baits was significantly higher in canopy near the edges of vine blocks so it seems likely there would have been a higher predator abundance had predation rate in the canopy been measured and observed in the work in this chapter.

5.5.5 Conclusion

This work in this chapter demonstrates that providing non-crop vegetation that suffers fewer disturbances may enhance biological control services such as predation of pest species.

The results of this study suggest that directly adjacent non-crop vegetation, such as that at the edge of vine-blocks, may provide habitat in vineyards for ground-foraging predatory arthropods and support a higher predation rate. This further supports the results in Chapter 4, which found local non-crop vegetation important in increasing the rate of predation.

These results support the hypothesis that disturbance and lack of habitat caused by herbicide-treated areas lowers the rate of predation at the vine-block scale.

Unfortunately this effect was apparent only in the 'model' species, the *H. zea* egg baits. The vine pest species *E. postvittana* egg baits showed no such difference in predation rate. However, although the predation rate was not higher, predators did spend more time on baits in the control strips than in herbicide strips and this may reflect a temporal effect on the preference of eggs by predators. The ryegrass

(control) strips and herbicide strips were both 5m in width each, and for *P. opilio* and *F. auricularia* this is not a large distance to cross (Frank *et al.* 2007), therefore a lack of access to baits in neighbouring treatment strips is unlikely to have been a factor.

Further work examining the effects of disturbance on biological control through 'normal' crop management is needed. This is likely to be important for both predatory arthropods and the growers, as 'selective' disturbance such as alternate strips of harvested and non-harvested crop may improve predation rates in unharvested crops (Hossein *et al.* 2002) and would be a simple change in the habitat management strategy employed.

Vine-blocks of different grape varieties harvesting at different times does occur. However, it is unlikely that the key predator species here are particularly vagile so are unlikely to move between vine-blocks rapidly enough to support this selective harvest idea. Wine grapes are harvested based on ripeness (sugar levels; brix) so leaving unharvested areas for later attention is not feasible. Also it is unlike that this management would ameliorate pest damage, which, even for staggered harvesting, would have already affected that crop.

Chapter 6:

Discussion

6.1 Introduction

The number of studies of landscape- and local-scale effects of non-crop vegetation on natural enemies in agriculture within the discipline of conservation biological control (CBC) is rising, often with findings of enhanced CBC where non-crop vegetation is more abundant and diverse. However, a general premise of having more non-crop vegetation in agricultural crops and landscapes may not be cost effective for growers to implement (Cullen *et al.* 2008). Increasing non-crop vegetation may also not target all effective natural enemies in an agricultural system. For example, buckwheat planted in vineyards provide supplementary resources to *D. tasmanica*, a well-known parasitoid of the light brown apple moth (*E. postvittana*) (Berndt *et al.* 2006), but may not provide support to affect higher abundance and density of earwigs, which have also been shown to be effective natural enemies of *E. postvittana* in vineyards (Frank *et al.* 2007). Effects on the pests themselves (longevity, fecundity etc.) are also needed as without this information, the effects of floral resources, for example, may have an overall negative effect.

Research focusing on non-crop vegetation effects on parasitoids, predators and pests in agricultural systems at both landscape and field scales has included work on many pest species including *E. postvittana* and *H. zea* (Frank *et al.* 2007, Stephens *et al.* 2008), potato moth (Baggen and Gurr 1998), rape pollen beetle (Thies and Tscharntke 1999), *M. brassicae* (Bianchi *et al.* 2005), soybean aphid (Gardiner *et al.* 2009) and diamond-back moth (Jonsson *et al.* 2012). Positive effects of different types of non-crop vegetation on natural enemies at the landscape scale have been well documented; however, there are also studies in which no effect of the landscape non-crop vegetation is shown, and even potentially negative effects have been found (Bianchi *et al.* 2006, Rand *et al.* 2012). Non-crop vegetation effects on natural enemies at the local scale have been similarly well studied, in different agricultural systems, with both existing and added non-crop vegetation.

However, it may be that provision of non-crop vegetation is more effective at enhancing pest control by natural enemies when combined with a low disturbance habitat management strategy. This may affect ground dwelling generalist predator species in particular, as most are non-flying and cannot easily escape the mechanical and chemical disturbances often used in ‘conventional’ agricultural practices (Thomas *et al.* 1991, Jonsson *et al.* 2012).

The aim of the work in this thesis was to evaluate, in multiple and single vineyards in a landscape, the effects of non-crop vegetation on predator numbers and predation rates at both the landscape and the local scale. Effects of disturbance upon predators by ‘conventional’ habitat management practices were assessed. Overall, an understanding of what biological control the landscape and local scale non-crop vegetation may already provide was achieved. It is hoped that this will guide ‘next steps’ for growers to incorporate or adapt into their existing habitat management strategies.

In this discussion, the results of the experiments described in this thesis are examined within the context of CBC. Enhancement of CBC by landscape and local non-crop vegetation was measured by changes in pest populations (Chapter 2), rates of predation (Chapters 3, 4, 5) and video-monitored feeding behaviour of predators (Chapter 5). Potential effects on CBC of non-crop vegetation at the landscape scale (Chapters 2 and 3), local scale (Chapters 4 and 5), and as part of a ‘conventional’ habitat management strategy (Chapter 5) are addressed. To close, potential future research that may answer new questions posed by this research is considered.

6.2 The ability of non-crop vegetation to provide CBC at the landscape and local scale

As discussed in Chapter 1, CBC can be enhanced by manipulating ‘bottom-up’ and ‘top-down’ habitat management strategies (Gurr *et al.* 2000) to produce effects consistent with either the ‘resource concentration’ hypothesis or the ‘natural enemies’ hypothesis (respectively) (Root 1973). To evaluate the success of non-crop vegetation in improving CBC at landscape and local scales, the results from each experiment will be determined to have been successful if they can be described as

being either representative of the ‘resource concentration’ hypothesis or the ‘natural enemies’ hypothesis, and if they show a significant positive effect of either hypothesis on pest ‘population’ reduction.

It was not the aim of this work to develop practices to reduce pest populations to below economic thresholds. This was because a) justified and published thresholds do not exist in the literature for the study system and b) the aim was to explore mechanisms and possible pointers for future practices.

Results of Chapter 2 revealed significantly lower abundance of the herbivorous pest *C. zealandica* adults near shelterbelts at both the landscape and the local scale. These results are most appropriately evaluated using the ‘resource concentration’ hypothesis, as there were no natural enemies in this experiment, and it was differences in pest abundance that were measured. There was a significant effect of shelterbelts reducing adult grass grub numbers. This effect was a mean reduction in the number of adult grass grubs of approximately 20% overall, from the shelterbelts’ influence. These results are an example of the ‘resource concentration’ hypothesis and they also support the hypothesis of the experiment; that there would be a lower abundance of pests in vines near shelterbelts. Typically, the resource concentration hypothesis has referred to non-crop plants within the crop, which disrupt, or attenuate the normal visual cues herbivores use to find food, and therefore reduce their likelihood of finding the crop plants (Root 1973). The shelterbelts in the current work were not within the crop, they were at the crop edges; however, they do disrupt the normal visual feeding cues of *C. zealandica*, and reduce its access to the vine plants. It is in this context that shelterbelts are considered an example of the ‘resource concentration’ hypothesis. Therefore, from these results it can be concluded that shelterbelts may provide an effective barrier against *C. zealandica* (adult) presence in vineyards (Wratten *et al.* 2003, Tsitsilas *et al.* 2006).

Changes in predation rate in vineyards at the landscape scale were investigated in Chapter 3 and at the local scale in Chapter 4. As the rate of predation of ‘sentinel’ lepidopteran eggs (*E. postvittana* and *H. zea*) was the measure of change, it was the ‘natural enemies’ hypothesis tested in these experiments. There was no significant effect of any of the landscape variables on the rate of predation, nor were the

landscape-scale results representative of the ‘natural enemies’ hypothesis. The experimental hypothesis that there would be higher predation in vineyards with more complex parts of the landscape nearby was also not supported. Therefore the results of the Chapter 3 landscape scale experiment did not meet the requirements for success in aiding in CBC. However, there was a significantly higher predation rate at the local scale, as shown in Chapter 4. The predation rate of *E. postvittana* and *H. zea* eggs at the edges of the vine blocks was significantly higher than in the centre, in baits on the ground. There was also higher predation of *H. zea* eggs at the edges of the vine block in the canopy of the vines. There was a slightly lower but still significant positive effect of the vineyard non-crop vegetation between the vine rows on the predation rate of *E. postvittana* sentinel egg baits. As these results are both representative of the ‘natural enemies’ hypothesis, and have shown significant positive effects, the non-crop vegetation at the vine block edges, and between the rows may be described as enhancing CBC in the vineyards. They also support the experimental hypothesis that there will be higher predation adjacent to non-crop vegetation at the local scale.

Chapter 5 also measured the rate of predation of the same two lepidopteran species’ ‘sentinel’ egg baits at the edge and centre of a vine-block; however, this time herbicide-treated and ‘control’ areas were assigned to the vine-block, and the predation rate of the sentinel egg baits was assessed in these areas as well. The control plots were in areas of normal vineyard management in the vine block, while the herbicide-treated areas were bare. Again (as in Chapter 4) the rate of predation was significantly higher at the edges of the vine block than at the centre for *H. zea* eggs. This effect on predation rate at the vine block edge did not occur in *E. postvittana* eggs. Similarly, although the predation rate of *H. zea* eggs was significantly higher in control plots than in the herbicide treated plots, as was expected in the experimental hypothesis, this effect was not also found for *E. postvittana* eggs. The non-crop vegetation in the vine block therefore may enhance CBC.

6.3 Effects of non-crop vegetation on arthropods in vineyards at the landscape and local scale

The above evaluation (6.2) indicates that landscape non-crop vegetation does need to be considered as a contributor to conservation biological control (CBC) in vines in this study. While landscape scale non-crop vegetation had no effect on the predation rate, landscape scale non-crop vegetation has been shown it can be successful in enhancing CBC at larger spatial scales (Thies and Tschardt 1999, Thies *et al.* 2003, Gardiner *et al.* 2009) than those employed in this work, therefore positive effects may be detected under further experimentation. However, the predation rate was clearly enhanced by non-crop vegetation at the local scale. This effect was mediated through edge effects of the non-crop vegetation in the vine-block (Rand *et al.* 2006). The significantly lower numbers of the pest *C. zealandica* in vines near shelterbelts indicate that cultural methods of control may inhibit this pest in Waipara vineyards.

Non-crop vegetation in the landscape had no effect on predation of either *E. postvittana* or *H. zea* eggs, in the canopy or on the ground in vineyards. This is also the case in landscapes with high complexity (Tschardt *et al.* 2005), and the Waipara valley landscape may be complex enough to support relatively high predation to start with. The ‘Greening Waipara’ project (Chapter 1) has been steadily enhancing the area with large patches of native plants and providing information to growers and winery visitors, indicating a general awareness of a need for diversity and more complex agricultural regions. The size of the Waipara valley ‘landscape’ may not support large enough differences within the area to affect predators and the entire landscape of the Waipara valley winegrowing region may be affected by the same processes (Gardner *et al.* 1987). It is possible that the Waipara valley has functional connectivity between areas of high complexity and biodiversity, thereby ‘distributing’ any effects of the landscape non-crop vegetation that may affect pest populations throughout the landscape (Tischendorf and Fahrig 2000). The apparent lack of a landscape scale biocontrol effect in this work, may also be explained by the predators (*P. opilio* and *F. auricularia*) observed feeding on sentinel egg baits (Chapter 5). Both species are considered to have low dispersal behaviour (Moerkens *et al.* 2010) and are likely only affected by their immediate surroundings.

However, non-crop vegetation at the landscape scale did affect the pest *C. zealandica*. Shelterbelts can be barriers to arthropods flying toward the crop (Wratten *et al.* 2003), and can also limit their access to neighbouring crops (Mauremooto *et al.* 1995).

It is also possible that shelterbelts contributed to the increase in predation at the edges of vineyards at the local scale, even though there was no significant effect of this in the analysis. This ‘edge effect’ increased the predation rate significantly when compared to the centre of a vine-block in each of 25 vineyards (Chapter 4) and in a single vineyard the next season (Chapter 5). The ‘edge effect’ in this study was considered to be a function of a lack of disturbance and this is further supported by evidence that the rate of predation also increased in lesser-disturbed ‘control’ plot areas in the experiment in Chapter 5. This effect was not shown for *E. postvittana*, which was of particular interest, as it is one of relatively few vine pests occurring in the Waipara winegrowing region. Potentially, the level of disturbance to which the vine block had already been subjected had influenced the population of predators in some way already. It is possible that there may not have been enough predators present to effect a change in predation of *E. postvittana* eggs if *H. zea* eggs were preferred, particularly considering the limited time available to measure a difference (Chapter 5). There were only two different species of predators identified using video monitoring techniques, and it may be possible that other predators had suffered from the disturbance and not recolonized that vine-block (Thorbek and Bilde 2004). The earwig (*F. auricularia*) has been found to be a voracious predator of *E. postvittana* larvae in the canopy of vines (Frank *et al.* 2007) and may have found refuge in the canopy during the mowing and herbicide application for this trial.

6.4 Future research

Local non-crop vegetation increased predation of pest eggs by natural enemies. To understand the mechanism of this and therefore the implications for CBC, detailed information on both the quality and the quantity of this vegetation is needed. The lack of disturbance in areas of non-crop vegetation is likely a factor in increasing predation; however, predators in the vine-blocks can be expected to seek out resources from vegetation that best meets their requirements. Predation of *H. zea* in the vine canopy was significantly higher at the edge than the centre; however, this

was not the case for *E. postvittana*. As the canopy is where most eggs were likely to be laid, information on improving predation rates of the eggs in the canopy is needed. *H. zea* may have been taken preferentially, as its eggs are not laid in batches and coated in a waxy substance as are *E. postvittana* eggs. It is also possible that *H. zea* eggs were favoured because they may be nutritionally superior (Eubanks and Denno 2000). Therefore this information is necessary as it is possible that the presence of *H. zea* eggs changed the feeding behaviour of the predators in the canopy, and these results may not reflect what would happen in the vineyard naturally, particularly because *H. zea* is not a pest of vines. *F. auricularia* was a voracious predator of *E. postvittana* larvae in the canopy of a vineyard at Lincoln University, Canterbury, New Zealand (Frank *et al.* 2007) and information on their voracity in egg predation is also needed. *P. opilio* and *F. auricularia* are likely not the only predators in the vine-block area and other species, particularly mite (Acaria) and ant (Formicidae) species have been found to be effective predators in vineyards (Frank *et al.* 2007). Further video based work on feeding behaviour of predators in vineyards is needed to determine which other predators are present and effective, particularly the mite species, as they have been shown in laboratory work to have a commensal feeding relationship with *P. opilio* (Merfield *et al.* 2000). Information on whether this same relationship is found in vineyards is needed, as this relationship may help increase CBC. Harvestmen were observed driving away earwigs (Chapter 5) in the present work, and behavioural interactions between these and other predators in vineyards may contribute to or inhibit CBC; i.e., inter-guild interactions. It is also possible that harvestmen or earwigs were responsible for inter-guild predation of other types of predators that may have otherwise taken the sentinel baits (Rosenheim *et al.* 1993, Traugott *et al.* 2011), and further video-based work may detect these types of interactions.

As growers are likely to have to subject their vineyards to some level of disturbance other than harvesting, further information on how the predators in the vineyard are affected by these different practices, such as herbicide applications and mowing, is also necessary. Potentially, some degree of disturbance could be used selectively to move predators from one part of the crop to another (Hossain *et al.* 2007), which may increase CBC success.

Landscape scale effects of non-crop vegetation were observed in changes of grass grub abundance. Shelterbelts seemed to inhibit or prevent *C. zealandica* adult beetles' access to vine rows both at the landscape and local scales. However, it is still not known from where *C. zealandica* was flying. As the Waipara valley is largely pasture, and many of the vineyards themselves are planted in old pasture sites, it is possible that *C. zealandica* is emerging from soil within the vineyard itself; therefore, further field experimentation to ascertain the role of shelterbelts would be necessary. Insects can be 'tagged' with rubidium chloride (RbCl), an elemental marker that can be applied to target plants (Kobelt *et al.* 2009). It has been shown to be effective in marking herbivorous invertebrates; however, it would be difficult to track these insects with RbCl as the adults do not feed on the pasture they emerge from. *C. zealandica* could be trapped on both sides of the shelterbelts, therefore it would be important to investigate whether they are definitely stopping grass grub passage to the vines and if there is less foliage damage associated with the shelterbelts presence. Inoculating the vineyard soil with *Serratia entomophila* bacterium to lower the abundance of the pest during the larval stage may also be an option (Townsend *et al.* 2004), with more trapping to ascertain any difference in abundance. As planting shelterbelts, rows of dense, woody evergreen species, takes time and incurs a cost, it would be logical to find out if these landscape and local 'structures' provide a barrier, for other flying pest species. This information may be necessary and helpful for other cropping systems as well (Bhar and Fahrig 1998).

6.5 Conclusions

The results from this study indicate that non-crop vegetation at the local scale does enhance biological control and provide information and direction on what could be improved in habitat management strategies for more effective and successful CBC in vines in New Zealand and elsewhere.

Local scale edge effects and other lesser-disturbed non-crop vegetation, such as that between vine rows, can increase predation in vineyards. However, the results from this study demonstrate that the egg masses of *E. postvittana*, the main pest arthropod species of Waipara valley vines, may not be subject to this increased predation in the vine canopy, which is where the eggs would be oviposited naturally. However,

predation of *H. zea* in the canopy did increase with non-crop vegetation at the edge of the vine-block (Chapter 4). While not a pest in vines, eggs of *H. zea* provide an appropriate comparative model for invasive pest species seen as a threat to New Zealand and Australian vines. For example, the European grape moth (*L. botrana*), one of the most destructive vine pests in the Palearctic region, was discovered in California in 2009 (Gilligan *et al.* 2011) and is considered to have the potential to invade other areas, such as Australasia. The damage it causes is similar to that of *E. postvittana*, with most economic losses due to the growth of *B. cinerea* (bunch rot) (Chapter 1) on damaged grapes (Gilligan *et al.* 2011). However, unlike *E. postvittana*, *L. botrana* oviposits eggs singly, rather than in a mass, and use of *H. zea* eggs, which are also laid singly, therefore can simulate likely predation events on the pest species. *L. botrana* is polyphagous and other host plants include kiwifruit and apples, which are also large export industries in New Zealand. The glassy-winged sharp-shooter (*H. coagulata*) is another pest species that spreads disease. It has potential to invade Australasia, as it has colonised California, French Polynesia and Hawaii from the Southern U.S.A., and New Zealand and Australia are considered to have climates conducive to invasion (Hoddle 2004). In Tahiti, fewer than 2% of *H. coagulata* eggs were found parasitised, likely due to the lack of coevolved natural enemies there; therefore, it may be that predation of *H. coagulata* could be the predominant means of biological control. However, this inference must be balanced against the fact that ‘new association’ biocontrol of this type has been more successful than has orthodox classical biological control (O’Connell *et al.* 2012, Hajek 2004)

The potential for enhanced CBC for *E. postvittana* and potential pest species needs to be more fully explored as there are questions that need to be answered (see 6.4) before a particular habitat management strategy could be advised. This is in the context to which extent non-crop vegetation in vineyards can be expressed as a service-providing unit (SPU) (Luck *et al.* 2003), the unit required to precisely define an ES for an end-user stake-holder (Chapter 1) such as biological control, in this instance. An SPU is explained at a specified spatial or temporal scale with the consequences of deployment defined, acknowledging both social and scientific values as appropriate (Luck *et al.* 2003).

Landscape and local-scale effects of shelterbelts can lower *C. zealandica* abundance in vines, presumably by inhibiting the pests' progress through or over them. However, the benefit/cost analysis of planting shelterbelts to inhibit this pest would need to be fully explored before the value of these non-crop vegetation structures could be considered worthwhile. Similarly, the costs of attenuating the effects of disturbance, such as by fewer herbicide applications in the habitat manipulation strategy would also need to be investigated for practicality and economics before changes to management were applied. It is inconceivable that growers would contemplate changing woody vegetation on their own and neighbours land to ameliorate the effects of just this one, sporadic, pest.

This study was conducted in vineyards in one wine-growing region in New Zealand. However, other wine-growing regions in New Zealand have the same pests and diseases to manage so the information in this thesis may have broader application. *E. postvittana* is a pest in all wine-growing regions in New Zealand, and non-crop vegetation that may enhance CBC through higher predation rates could improve sustainable management of the pest. In previous work, successful outcomes in the Waipara and Marlborough wine-growing regions in supplementing floral resources in vineyards (Berndt *et al.* 2006) has led to buckwheat (*F. esculentum*) planted in all New Zealand wine regions, and in Australia also to enhance CBC. However, new field experimentation would be necessary in different cropping systems and should address non-crop vegetation in association with agricultural practices and their disturbance, as in this study, to understand predator dynamics, compared with those of parasitoids, and the potential for CBC. For example as mentioned above, New Zealand, like other countries, is subject to continuing invasive pests and diseases. Using an 'urgent response' strategy in response to each invasion will not be satisfactory. It would have more strategic value if the factors influencing the likelihood of these invaders' acquiring pest status were examined in the context of cropped and non-cropped aspects of the landscape.

New sustainable pest management technologies and practices that can easily be adopted and implemented by growers in all types of agriculture are increasingly necessary. These practices need to be grounded in ecological science and the benefits and negative aspects well understood for success in CBC. For example, there

is an urgent need for research on functional biodiversity to remain available in a form that growers can readily understand and deploy. The concept of an SPU as introduced above (Luck *et al.* 2003) is important in this context. Of equal importance is the ‘scalability’ (Kay *et al.* 2001), measuring the ease with which these processes can have value at a wider catchment or beyond. The work in this thesis is a contribution to that approach; there is a growing urgency to improve and place appropriate value on resources for sustainable management of agricultural land use, and this is supported by recent reviews on the future of world agriculture (Jordan *et al.* 2007, Landis *et al.* 2008, Vitousek *et al.* 2009).

References

- Altieri and Whitcomb. 1980. Weed manipulation for insect pest management in corn. *Environmental Management* 4:48-489 Springer-Verlag New York Inc.
- Araj S-E, Wratten S., Lister A. and Ghabeish I. 2011. Searching behavior of an aphid parasitoid and its hyperparasitoid with and without floral nectar. *Biological Control* 52(2):79–84
- Baggen L.R. and Gurr G.M. 1998. The Influence of Food on *Copidosoma koehleri* (Hymenoptera: Encyrtidae), and the Use of Flowering Plants as a Habitat Management Tool to Enhance Biological Control of Potato Moth, *Phthorimaea operculella* (Lepidoptera: Gelechiidae). *Biological Control* 11: 9–17
- Baggen L. R., Gurr G. M. and Meats A. 1999. Flowers in tri-trophic systems: mechanisms allowing selective exploitation by insect natural enemies for conservation biological control. *Entomologia Experimentalis et Applicata* 91:155-161.
- Begum M., Gurr G.M., Wratten S.D., Hedberg P. and Nicol H.I. 2003. The effect of floral nectar on the grapevine leafroller parasitoid, *Trichogramma carverae*. *Int. J. Ecol. Environ. Sci.* 30:3-12.
- Begum M., Gurr G.M., Wratten S.D., Hedberg P. and Nicol H.I. 2006. Using selective food plants to maximize biological control of vineyard pests. *J. Appl. Ecol.* 43:547-554.
- Bell V.A., Brightwell R.J. and Lester P.J. 2006. Increasing vineyard floral resources may not enhance localised biological control of the leafroller *Epiphyas postvittana* (Lepidoptera: Tortricidae) by *Dolichogenidea* spp. (Hymenoptera: Braconidae) parasitoids. *Biocontrol Science and Technology* 16(10):1031-1042

- Benton T.G., Vickery J. A. and Wilson J. D. 2003. Farmland biodiversity: is habitat heterogeneity the key? *Trends in Ecology and Evolution* 18:4
- Berndt L.A., Wratten S.D. and Scarratt S.L. 2006. The influence of floral resource subsidies on parasitism rates of leafrollers (Lepidoptera: Tortricidae) in New Zealand vineyards. *Biological Control* 37:50–55
- Bianchi F.J.J.A., van Wingerden W.K.R.E., Griffioen A.J., van der Veen M., van der Straten M.J.J., Wegman R.M.A. and Meeuwsen H.A.M. 2005. Landscape factors affecting the control of *Mamestra brassicae* by natural enemies in Brussels sprout. *Agriculture, Ecosystems & Environment* 107(2-3): 145-150.
- Bianchi, F. J. J. A., Booij C. J. H. and Tschamtker T. 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society B: Biological Sciences* 273(1595): 1715-1727.
- Bianchi F. J. J. A., Goedhart P. W. and Baveco J. M. 2008. Enhanced pest control in cabbage crops near forest in The Netherlands. *Landscape Ecology* 23: 595-602
- Bhar R. and Fahrig L. 1998. Local vs. landscape effects of woody field borders as barriers to crop pest movement. *Conservation Ecology* [online] 2(2): 3. Available from the Internet URL: <http://www.consecol.org/vol2/iss2/art3>
- Bohlen P. J. and Barrett G. W. 1990. Dispersal of the Japanese Beetle (Coleoptera: Scarabaeidae) in Strip-Cropped Soybean Agroecosystems. *Environmental Entomology* 19(4):955-960
- Booth L. H., Hodge S. and O'Halloran K. 2001. Use of Biomarkers in Earthworms to Detect Use and Abuse of Field Applications of a Model Organophosphate Pesticide. *Bulletin of environmental contamination and toxicology* 67(5):633-640

- Bowden, J., and Dean G. J. W. 1977. The distribution of flying insects in and near a tall hedgerow. *Journal of Applied Ecology* 14: 343-354.
- Bugg R.L. and Wilson L.T. 1989. *Ammi visnaga* (L.) Lamarck (Apiaceae): Associated Beneficial Insects and Implications for Biological Control, with Emphasis on the Bell-Pepper Agroecosystem. *Biological Agriculture and Horticulture* 6:241-268
- Capinera, J. L., Weissling T. J. and Schweizer E. E. 1985. Compatibility of intercropping with mechanized agriculture: effects of strip intercropping of pinto beans and sweet corn on insect abundance in Colorado. *Journal of Economic Entomology* 78: 354-357.
- Campbell N. A., Reece J. B. and Mitchell L. G. 1999. The evolution of populations. Pages 428-444 in E. Mulligan, editor. *Biology* fifth edition. Addison-Wesley, New York.
- Carpenter S. R. and Kitchell J. F. 1993. The trophic cascade in lake ecosystems Cambridge university press, Cambridge Corbett A. and Rosenheim J. A. 1996. Impact of natural enemy overwintering refuge and its interaction with the surrounding landscape. *Ecological Entomology* 21: 155–164.
- Costanza, R., R. D. Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S.Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253-260.
- Cullen, R., Warner K. D., Jonsson M. and Wratten S. 2008. Economics and adaptation of conservation biological control. *Biological Control* 42:272-280
- Cullen R., Forbes S., Grout R. and Smallman C. Evaluation of Conservation Biological Control Innovation in Winegrowing. Paper presented at the 2010 New Zealand Agriculture and Resource Economics Society Conference

- Danne A., Thomson L. J., Sharley D. J., Penfold, C. M. and Hoffmann A. A. 2010. Effects of Native Grass Cover Crops on Beneficial and Pest Invertebrates in Australian Vineyards. *Environmental Entomology* **39**(3): 970-978.
- Daily, G. C. 1997. Introduction: What are ecosystem services? Pages 1-10 in G. C. Daily, editor. *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Covelo, USA.
- De Bach P. 1964. *Biological control of insect pests and weeds*. Reinhold Publishing Corporation, New York.
- den Belder E., Elderson J., van den Brink W.J. and Schelling G. 2002. Effect of woodlots on thrips density in leek fields: a landscape analysis. *Agriculture, Ecosystems and Environment* 91:139–145
- Dennis, P., and Fry G. L. A. 1992. Field margins: can they enhance natural enemy population densities and general arthropod diversity on farmland? *Agriculture, Ecosystems and Environment* 40: 95-115.
- Dennis P. and Thomas M.B. 1994. Structural features of field boundaries which influence the overwintering densities of beneficial arthropod predators. *Journal of applied ecology* 31: 361-370
- Diaz, R., Knutson A. and Bernal J. S. 2004. Effect of the Red Imported Fire Ant on Cotton Aphid Population Density and Predation of Bollworm and Beet Armyworm Eggs. *Journal of Economic Entomology* 97(2): 222-229.
- Dix M. E., Hodges L., Brandlez J. R., Wright R. J. and Harrell M. O. 1997. Effects of Shelterbelts on the Aerial Distribution of Insect Pests in Muskmelon. *Journal of sustainable agriculture* 9:5-24
- Epstein D.L., Zack, R.S., Brunner J.F., Gut, L. and Brown J.J., 2001. Ground beetle activity in apple orchards under reduced pesticide management regimes. *Biol. Control* 21, 97–104

- Eubanks M.D. and Denno R.F. 2000. Host plants mediate omnivore-herbivore interactions and influence prey suppression. *Ecology* 81: 936-947.
- Fiedler A. K., Landis D. A. and Wratten S. 2008. Maximizing ecosystem services from conservation biological control: The role of habitat management. *Biological Control* 45(2): 254-271.
- Frampton G. K., Cilgi T., Fry G. L. A. and S. D. Wratten. 1995. Effects of grassy banks on the dispersal of some carabid beetles (Coleoptera: Carabidae) on farmland. *Biological Conservation* 71: 347-355.
- Frank S.D. and Shrewsbury P.M. 2004. Effect of conservation strips on the abundance and distribution of natural enemies and predation of *Agrotis ipsilon* (Lepidoptera: Noctuidae) on golf course fairways. *Environmental Entomology*. 33, 1662–1672.
- Frank S., Wratten S. D., Sandhu H. and Shrewsbury P.M. 2007. Video analysis to determine how habitat strata affects predator diversity and predation of *Epiphyas postvittana* (Lepidoptera: Tortricidae) in a vineyard. *Biological Control* 41(2): 230-236.
- Fry G. and Sarlöv-Herlin I. 1997. The ecological and amenity functions of woodland edges in the agricultural landscape; a basis for design and management 37:45–55
- Gardiner M.M., Landis D.A., Gratton C., Schmidt N.P., O'Neal M., Mueller E., Chacon J., Heimpel G. E. and DiFonzo C. D.. 2009. Landscape composition influences patterns of native and exotic ladybeetle abundance. *Diversity and Distributions* 15:554–564.
- Gardiner MM, Landis DA, Gratton C, DiFonzo CD, O'Neal M, Chacon J. M., Wayo M.T., Schmidt N.P., Mueller E. and Heimpel G. E. 2009. Landscape diversity enhances biological control of an introduced crop pest in the north-central USA. *Ecological Applications* 19:143–154.

- Gilligan T. M., Epstein M.E., Passoa S. C., Powell J. A., Sage O.C. and Brown J.W. 2011. Discovery of *Lobesia botrana* in California: an invasive species new to north America (Lepidoptera: Tortricidae). *Proceedings of the Entomological Society of Washington* 113(1): 14-30
- Given B.B. 1966. The genus *Costelytra* Given (Melolonthinae: Coleoptera) including descriptions of four new species. *N.Z. Journal of Sciences* 9: 373-390.
- Glenn, D.C. and Milsom, N.F. 1978. Survival of mature codling moth (*Cydia pomonella*) on apple trees and on the ground. *Annual Applied Biology* 90:133–146
- Golden, D.M. and Crist, T.O. 1999. Experimental effects of habitat fragmentation on old-field canopy insects: community, guild and species responses. *Oecologia* 118, 371–380.
- Greathead, D. J. and A. H. Greathead. 1992. Biological control of insect pests by insect parasitoids and predators: the BIOCAT database. *Biocontrol News and Information* 13:61- 68.
- Gurr, G. M. and Wratten, S.D. *ed.* 2000: *Biological Control: Measures of Success*. Kluwer Academic Publishers, The Netherlands.
- Gurr G. M., Scarratt S., Jacometti M. A. and Wratten S. D. 2007. Management of pests and diseases in New Zealand and Australian Vineyards. Pages 392-398 in C. Vincent, M. S. Goettel, and G. Lazarovits, editors. *Biological Control: a global perspective*. CAB International, Oxfordshire.
- Hajek A. E. 2004. *Natural Enemies: An Introduction to Biological Control*. Cambridge University Press, Cambridge, UK
- Halaj J., Cady A.B. and Uetz G.W. 2000. Modular Habitat Refugia Enhance Generalist Predators and Lower Plant Damage in Soybeans. *Environmental Entomology*. 29(2): 383-393

- Hawkes, C. 1973. Factors affecting the aggregation of the adult cabbage root fly (*Erioischia bouché*) at hedges. *Journal of Applied Ecology* 10: 695-703.
- Hoddle M.S. 2003. Predation behaviors of *Franklinothrips orizabensis* (Thysanoptera: Aeolothripidae) towards *Scirtothrips perseae* and *Heliothrips haemorrhoidalis* (Thysanoptera: Thripidae). *Biological Control* 27:323–328
- Holland, J. and Fahrig, L. 2000. Effect of woody borders on insect density and diversity in crop fields: a landscape scale analysis. *Agricultural Ecosystems and Environment* 78 :115–122.
- Holland J.M. and Luff M.L. 2000. The Effects of Agricultural Practices on Carabidae in Temperate Agroecosystems. *Integrated pest management reviews* 5(2)109-129
- Holmes, D. M. and G. W. Barrett. 1997. Japanese beetle (*Popillia japonica*) dispersal behavior in intercropped vs. monoculture soybean agroecosystems. *American Midland Naturalist* 137: 312-319.
- Hossain Z., Gurr G. and Wratten S. 2000. The potential to manipulate the numbers of insects in lucerne by strip cutting. *Australian Journal of Entomology* 39:39–41
- Hossain Z., Gurr G.M., Wratten S.D. and Raman A. 2002. Habitat manipulation in lucerne *Medicago sativa*: arthropod- pod population dynamics in harvested and ‘refuge’ crop strips. *Journal of Applied Ecology* 39: 445–454.
- Irvin N. A., Scarratt S. L., Wratten S. D., Frampton C. M., Chapman R. B., and Tylianakis J. M. 2006. The effects of floral understoreys on parasitism of leafrollers (Lepidoptera: Tortricidae) on apples in New Zealand. *Agricultural and Forest Entomology* 8:25-34
- Jackson T.A. and Klein M.G. 2006. Scarabs as Pests: A Continuing Problem. *The Coleopterists Bulletin* 60:102-119

- Jackson R.E., Bradley J.R., Van Duyn, J., Leonard B.R., Allen K.C., Luttrell R., Ruberson J., Adamczyk J., Gore J., Hardee D.D., Voth R., Sivasupramaniam S., Mullins J.W. and Head G. 2008. Regional assessment of *Helicoverpa zea* populations on cotton and non-cotton crop hosts. *Entomologia experimentalis et applicata* 126:89-106.
- Jackson T.A., Huger A.M. and Glare T.R. 1993. Pathology of Amber Disease in the New Zealand Grass Grub *Costelytra zealandica* (Coleoptera: Scarabaeidae). *Journal of Invertebrate Pathology* 61:123–130
- Jackson T. 1999. Factors in the success and failure of microbial agents for soil dwelling pests. *Integrated pest management* 4:281-285
- Jeffries M.J. and Lawton J.H. 1984. Enemy free space and the structure of ecological communities. *Biological Journal of the Linnean Society* 23:269-286
- Jordan N. G., Boody W., Broussard J. D., Glover D., Keeney B. H., McCown G., McIsaac M., Muller H., Murray J., Neal C., Pansing R. E., Turner K. and Wyse D. 2007. Sustainable development of the bioeconomy. *Science* 316:1570-1571.
- Jonsson M., Wratten S. D., Landis D. A. and Gurr G. M. 2008. Recent advances in conservation biological control of arthropods by arthropods. *Biological Control* 45:172-175.
- Kean J., Wratten S., Tylianakis J. and Barlow N. 2003. The population consequences of natural enemy enhancement, and implications for conservation biological control. *Ecology Letters* 6:604-612
- Kobelt A. J., Yen A. L. and Kitching M. 2009. Laboratory validation of rubidium marking of herbivorous insects and their predators. *Australian Journal of Entomology* 43: 204-209.

- Klug T., Gathmann A., Poehling H.M. and Meyhofer R. 2003. Area dependent effects of landscape structure on the colonisation of spinach cultures by the silver Y moth (*Autographa gamma* L., Lepidoptera: Noctuidae) in western Germany. IOBC wprs Bull 26:77–82.
- Kruess A. and Tschardt T. 1994. Habitat fragmentation, species loss, and biological control. *Science*. 264:1581–1584.
- Landis D. and Marino P. 1999. Landscape structure and extra-field processes: impact on management of pests and beneficials. In: Ruberson J.R, editor. Handbook of pest management. Marcel Dekker Inc; New York 79–104.
- Landis D. A., Gardiner M. M., van der Werf W. and Swinton S. M. 2008. Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. *Proceedings of the National Academy of Sciences of the United States of America* 105.
- Landis D. A., Wratten S. D. and Gurr G. M. 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology* 45:175-201.
- Lee C. L. and Heimpel G. E. 2005. Impact of flowering buckwheat on Lepidopteran cabbage pests and their parasitoids at two spatial scales. *Biological Control* 34:290-301.
- Lee J. C., Menalled F.D. and Landis D. A. 2001. Refuge habitats modify impact of insecticide disturbance on carabid beetle communities. *Journal of Applied Ecology* 38:472–483
- Lawrence W. S. 1982. Sexual dimorphism in between and within patch movements of a monophagous insect: *Tetraopes* (Coleoptera: Cerambycidae). *Oecologia* 53: 245-250.

- Letourneau D.K. and Altieri M.A. 1999. Environmental management to enhance biological control in agroecosystems. In: Bellows, T. and Fisher, T.W. (eds) Handbook of Biological Control. Academic Press, San Diego
- Lewis T. 1969. The diversity of the insect fauna in a hedgerow and neighbouring fields. *Journal of Applied Ecology* 6: 453-458.
- Logan D.P., Hill M. G., Connolly P.G., Maher B.J. and Dobson S.J. 2011. Influence of landscape structure on endemic cicadas in New Zealand kiwifruit orchards. *Agricultural and Forest Entomology* 13: 259-271
- Losey J.E and Denno R.F. 1998. Positive predator–predator interactions: enhanced predation rates and synergistic suppression of aphid populations. *Ecology* 79:2143–2152.
- Luck G.W., Daily G. C. and Ehrlich P. R. 2003. Population diversity and Ecosystems Services. *Trends in Ecology and Evolution* 18 (7) 331-335
- Mauremooto, J. R., Wratten S. D., Worner S. P. and Fry G. L. A. 1995. Permeability of hedgerows to predatory carabid beetles. *Agriculture, Ecosystem and Environment* 52: 141-148.
- Menalled F. D., Lee J. C. and Landis D. A. 2001. Herbaceous filter strips in agroecosystems: implications for carabid beetle (Coleoptera: Carabidae) conservation and invertebrate weed seed predation. *Great Lakes Entomology* 34: 77-91
- Merfield C.N., Wratten S.D. and Navntoft S. 2004. Video analysis of predation by polyphagous invertebrate predators in the laboratory and field. *Biological Control* 29, 5–13.
- Merton J.M. 1982. Interactions of the tachinid, *Prociesso cana* with its host the New Zealand grass grub, *Costelytra zealandica*. Proceedings of the third Australasian conference on grassland invertebrate ecology: 161-168.

- Miñarro M. and Dapena E. 2003 Effects of groundcover management on ground beetles (Coleoptera: Carabidae) in an apple orchard. *Applied Soil Ecology* 23:111–117
- Moerkens R., Leirs H., Peisens G. and Gobin B. 2010. Dispersal of single- and double-brood populations of the European earwig, *Forficula auricularia*: a mark-recapture experiment. *Entomologia Experimentalis et Applicata* 137(1)19-27
- Nicholls C.I., Parrella M. and Altieri M.A. 2000. Reducing the abundance of leafhoppers and thrips in a northern California organic vineyard through maintenance of full season floral diversity with summer cover crops. *Agricultural and Forest Entomology* 2:107-113
- Nicholls C.I., Parrella M. and Altieri M.A. 2001. The effects of a vegetational corridor on the abundance and dispersal of insect biodiversity within a northern California organic vineyard. *Landscape Ecology* 16:133–146
- O’Connell D.M., Wratten S.D., Pugh A.R. and Barnes A-M. 2012. ‘New species association’ biological control? Two coccinellid species and an invasive psyllid pest in New Zealand. *Biological Control* 62(2) 86-92
- O'Rourke M.E., Rienzo-Stack K. and Power A.G. 2011. A multi-scale, landscape approach to predicting insect populations in agroecosystems. *Ecological Applications* 21:1782–1791
- Östman Ö., Ekbom B. and Bengtsson J. 2001. Landscape heterogeneity and farming practice influence biological control. *Basic Applied Ecology* 2:365–371.
- Östman Ö., Ekbom B., Bengtsson J. and Weibull A.C. 2001. Landscape complexity and farming practice influence the condition of polyphagous carabid beetles. *Ecological Applications* 11:480–488.

- Outward R., Sorenson C.E. and Bradley Jr. J.R. 2008. Effects of Vegetated Field Borders on Arthropods in Cotton Fields in Eastern North Carolina. *Journal of Insect Science* 8:9
- Pfannenstiel R.S. and Yeorgan K.V. 2002. Identification and Diel Activity Patterns of Predators Attacking *Helicoverpa zea* (Lepidoptera: Noctuidae) Eggs in Soybean and Sweet Corn. *Environmental Entomology* 31(2): 232-241
- R Development Core Team. 2005. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
- Rodgers J.L. and Nicewander W.A. 1988. Thirteen ways to look at the correlation coefficient. *American Statistics* 42:59-66
- Root R. B. 1973. Organization of a plant- arthropod association in simple and diverse habitats: the fauna of collards (*Brassica oleracea*). *Ecological monographs* 43:95-120.
- Rosen D. and De Bach P. 1991. *Biological Control by Natural Enemies*, 2nd ed. Cambridge University Press , London.
- Rosenheim J. A., Wilhoit L. R. and Armer C. A. 1993. Influence of intraguild predation among generalist insect predators on the suppression of an herbivore population. *Oecologia* 96: 439-449.
- Scarratt S. 2005. Enhancing the biological control of leafrollers (Lepidoptera: Tortricidae) using floral resource subsidies in an organic vineyard in Marlborough, New Zealand. Doctor of Philosophy. Lincoln University, Lincoln, New Zealand.
- Schmidt M.H., Roschewitz I., Thies C. and Tschardt T. 2005. Differential effects of landscape and management on diversity and density of ground-dwelling farmland spiders. *Journal of Applied Ecology* 42:281–287

- Sharley D. J., Hoffmann A. A. and Thomson L. J. 2008. The effects of soil tillage on beneficial invertebrates within the vineyard. *Agricultural and Forest Entomology* 10(3): 233-243.
- Schmaedick M. A. and Shelton A. M.. 1999. Experimental evaluation of arthropod predation on *Pieris rapae* (Lepidoptera: Pieridae) eggs and larvae in cabbage. *Population Ecology* 28:439-444.
- Steck G.J. 2009. Spotted Wing Drosophila , *Drosophila suzukii* (Matsumura) (Diptera:Drosophilidae), a fruit pest new to North America.
http://pmtp.wsu.edu/downloads/Pest_Alerts-Spotted_Wing_Drosophila.pdf
- Steffan-Dewenter I. 2002. Landscape context affects trap-nesting bees, wasps, and their natural enemies. *Ecological Entomology* 27: 631–637.
- Stephens M. J., France C. M., Wratten S.D and Frampton C. 1998. Enhancing Biological Control of Leafrollers (Lepidoptera:Tortricidae) by Sowing Buckwheat (*Fagopyrum esculentum*) in an Orchard. *Biocontrol Science and Technology* 8(4): 547-558.
- Suckling D. M. and Brockerhoff E. G. 2010. Invasion Biology, Ecology, and Management of the Light Brown Apple Moth (Tortricidae). *Annual Review of Entomology* 55(1): 285-306.
- Thiery D. and Moreau J. 2005. Relative performance of European grapevine moth (*Lobesia botrana*) on grapes and other hosts. *Oecologia* 143:548-557
- Thies C. and Tschardt T. 1999. Landscape structure and biological control in agroecosystems. *Science* 285:893–895.
- Thies C., Steffan-Dewenter I. and Tschardt T. 2003. Effects of landscape context on herbivory and parasitism at different spatial scales. *Oikos* 101:18–25.

- Thies C., Roschewitz I. and Tschardt T. 2005. The landscape context of cereal aphid–parasitoid interactions. *Proc. R. Soc. B.* 285:203–210.
- Thomas W. P. 1963 A Natural Enemy of the Common Grass Grub, *Costelytra zealandica* White. *New Zealand Entomology* 3(2): 15- 18
- Thomas C.F.G. and Marshall E.J.P. 1999. Arthropod abundance and diversity in differently vegetated margins of arable fields. *Agriculture, Ecosystems and Environment* 72:131-144
- Thorbek P. and Bilde T. 2004. Reduced numbers of generalist arthropod predators after crop management. *Journal of Applied Ecology* 41:526–538
- Tilman D., Fargione J., Wolff B., Antonio C.D., Dobson A., Howarth R., Schindler D., Schlesinger W.H., Simberloff D. and Swackhamer D. 2001. Forecasting Agriculturally Driven Global Environmental Change. *Science* 292 (5515): 281-284
- Traugott M., Bell J.R., Raso L., Sint D. and Symondson W.O. 2012 (Epub 2011 Oct 10). Generalist predators disrupt parasitoid aphid control by direct and coincidental intraguild predation. *Bulletin of Entomological Research* 102(2): 239-47
- Tschardt T., Steffan-Dewenter I., Kruess A. and Thies C. 2002. Contribution of small habitat fragments to conservation of insect communities of grassland–cropland landscapes. *Ecol. Appl.* 12:354–363
- Tschardt T., Rand T.A. and Bianchi F.J.J.A. 2005. The landscape context of trophic interactions: insect spillover across the crop–noncrop interface. *Ann. Zool. Fenn.* 42:421–432.
- Tsitsilas A., Stuckey S., Hoffmann A.A., Weeks A.R. and Thomson L.J. 2006. Shelterbelts in agricultural landscapes suppress invertebrate pest. *Australian Journal of Experimental Agriculture* 46:1379–1388

- Tylianakis, J. M., Didham R. K. and Wratten S. D. 2004. Improved fitness of aphid parasitoids receiving resource subsidies. *Ecology* 85:658-666.
- Unelius C.R., Townsend R.J., Mundy D.C., Manning L.M., Jackson T.A. and Suckling D.M. 2008. Comparisons of traps and lures for monitoring grass grub, *Costelytra zealandica*. Proceedings of the 61st Conference of the NZ Plant Protection Society: 215-221
- van Driesche R. G. and T. S. Bellows. 1996. *Biological Control*. Chapman & Hall, New York.
- Vink C. J., Teulon D.A.J., McLachlan A.R.G. and Stufkens M.A.W. 2004. Spiders (Araneae) and harvestmen (Opiliones) in arable crops and grasses in Canterbury, New Zealand. *N.Z.J. Zool.* 31: 149-159.
- Vitousek P.M., Naylor R., Crews T., David M.B., Drinkwater L.E., Holland E., Johnes P.J., Katzenberger J., Martinelli L.A., Matson P.A., Nziguheba G., Ojima D., Palm C. A., Robertson G.P., Sanchez P.A., Townsend A.R. and Zhang F.S. 2009. Nutrient imbalances in agricultural development. *Science* 324(5934) 1519-1520
- von Ende, C.N. 1993. Repeated-measures analysis: Growth and other time dependent measures. In Scheiner, S. and I. Gurevitch (eds.) *The Design and Analysis of Ecological Experiments*. Chapman and Hall, pp. 113-137.
- Wratten S. D. 1988. The role of field boundaries as reservoirs of beneficial insects. Pages 144-150 in J. R. Park, editor. *Environmental management in agriculture*. Belhaven Press, New York, New York, USA.
- Wratten S.D., Bowie M. H., Hickman J.M., Evans A.M., Sedcole J.R. and Tylianakis J.M. 2003: Field boundaries as barriers to movement of hover flies (Diptera: Syrphidae) in cultivated land. *Oecologia* 134: 605-611.
- Zabel J. and Tschardt T. 1998. Does fragmentation of *Urtica* habitat affect phytophagous and predatory insects differentially? *Oecologia* 116:419-425

Zehnder G., Gurr G.M., Kuhne S., Wade M.R., Wratten S.D. and Wyss E. 2007.
Arthropod Pest Management in Organic Crops. *Annu. Rev. Entomol.* 52:57–
80