Possible impacts of climate change on biocontrol systems in New Zealand

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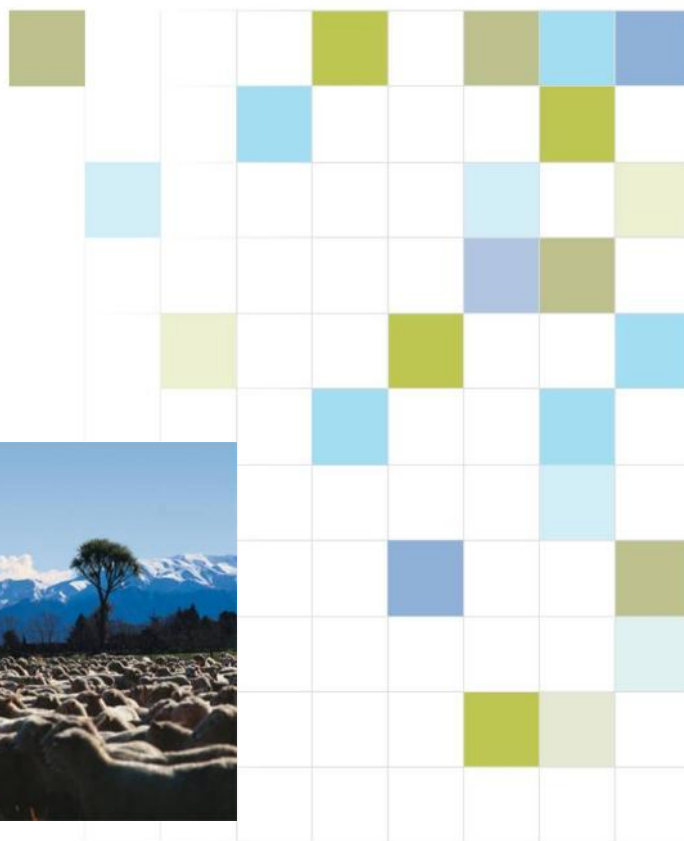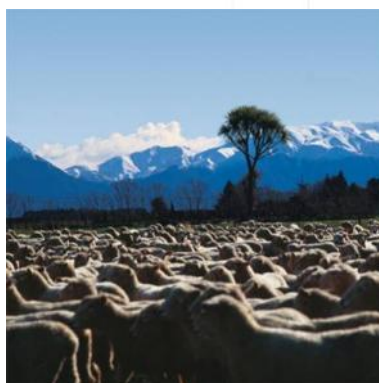
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Contents

1. Executive summary

- Climate change will have a direct effect on the location, nature and productivity of the pastures, crops, orchards and forests grown in the future in New Zealand. It is also changing the composition, distribution and phenology of the weeds and pests that compromise productivity and threaten the sustainability of both the productive and natural environments.

- By 2090, New Zealand's climate is predicted to be around 2°C warmer, on average, than in 1990. Rainfall is expected to increase in the west and decline in the east, and extreme weather events may be more common. The future distributions and local abundance of pests, weeds and their biocontrol agents will be influenced by these changes, together with changing patterns of land use and unchanging biological drivers such as seasonal daylength.

- New Zealand uses biocontrol to reduce greatly the need to use pesticides, provide cheap, long-term, self-sustaining control of pests, to conserve natural habitats and to foster sustainable systems dependent on natural processes with minimal intervention. It is a key component in integrated pest management programmes in some of our largest export crops such as kiwifruit and pipfruit.

- As climate changes, some cropping systems may have to move southward and the biocontrol systems will be able to move with them with little change in composition and impact. This could pose particular challenges to Maori enterprises that do not have a choice of moving their land as other growers could.

- Potential impacts of climate change were examined for five case study biocontrol systems.
  - Ragwort suppression by ragwort flea beetle is likely to fail when mean annual rainfall exceeds 1670mm. Climate change will increase the area in western regions where the biocontrol will fail but larger areas in northern North Island will attain suppression. In the eastern regions, the area increases where ragwort will not grow.
  - Tomato fruitworm is predicted to have a problematic autumn generation over much of the North Island, potentially limiting the viability of late corn and processing tomato crops. Given that the key parasitoid, *Cotesia kazak,* has not been effective at controlling this pest in warmer areas overseas, the future viability of the current IPM systems may be compromised.
  - Woolly apple aphid may achieve elevated densities in early spring after its parasitoid has been inactive, but greater suppression may be possible over the summer and autumn. The overall effectiveness of the IPM programme is predicted to be maintained, but with increasing importance of an insecticide application in spring.
  - The current success of lucerne weevil biocontrol may be compromised as New Zealand's climate approaches that of South Australia, where the biocontrol agent currently fails to suppress the pest.
  - Continuing biocontrol suppression of the Argentine stem weevil may rely on local adaptation of the parasitoid biotype complex. The low genetic variability of many other biocontrol agent populations may limit their ability to adapt successfully to future conditions.

- To ensure biocontrol continues as a mainstream pest management tool in the productive and environmental sectors, the following needs to be considered:

- Refuge habitats provided within the agricultural landscape that support a high abundance and diversity of predators and parasitoids and provide a buffer against the perturbations of extreme weather events.
- Pre-emptive action against "sleeper pests" (species already in New Zealand but kept in check by host unavailability and low temperature). Biocontrol should be investigated for those that are likely to become serious pests under climate change.
- A review of existing IPM/IFM systems to identify areas of most risk from climate change in each system and how to address them E.g. by introducing additional species of biocontrol agents for existing pests.
- Risk assessment and regulatory approval for introductions of new genetic lines for introduced biocontrol agents founded by few individuals. This will lessen potential negative impacts of climate change through greater genetic variation and potential for adaptation.
- Border biosecurity and surveillance in 'at risk' localities, backed by rapid response, to defend against the increased risk that the frequent subtropical "door knockers" become permanently established.
- Predictive models used to optimise the benefits of biocontrol, from the planning of long-term land uses and optimal timing and sequence of crops in a district to the augmentation of systems through the introduction of new natural enemies.

2.   Introduction

The purpose of this study is to provide expert opinion and case study examples of the likely responses of biocontrol (biological control) agents and biocontrol systems to key climate change threats. The focus is on the impact on the land-based sectors, in particular the productive sector. This report is written for central and local government, land managers in both the land-based productive and environment sectors, for whom the information is relevant when planning long-term management of weeds and invertebrate pests. It was commissioned by the Ministry of Agriculture and Forestry.

Climate change will not only have a direct effect on the location, nature and productivity of the pastures, crops, orchards and forests of the future. It is also changing the composition, distribution and phenology of the weeds and pests that compromise productivity and threaten the sustainability of both the productive and natural environments. Furthermore, the effectiveness of some of the natural enemies controlling the pests will change. The predictions are that the frequency and intensity of pest outbreaks will increase as climate becomes more variable and disrupts the stability of existing biocontrol systems (Stireman et al. 2005).

This section of the report describes why biocontrol is important to the New Zealand economy, and discusses the scenarios used as the bases of possible future changes in drought risk. Section 3 gives the reader an overview of the priority biocontrol systems that minimize the impact of weeds and pests in New Zealand's land-based sectors. Section 4 combines a review of the international scientific literature on the impact of climate change on biocontrol systems in temperate climates elsewhere in the world with New Zealand opinion and examples of what is most likely to occur here. Section 5 gives the results of five case studies used to explore in more detail how climate change may influence geographical distribution and biocontrol impact. Sections 6 and 7 summarise the findings and outline what needs to be done to ensure biocontrol continues to be a mainstream weed and pest management option in the future. List of references (Section 9) and contributors (Section 10) are also supplied.

2.1   Why biocontrol is important to New Zealand

Biocontrol is a method of using natural enemies to control pests (including insects, mites, weeds and plant diseases) through predation, parasitism, herbivory, or other natural mechanisms. Classical biocontrol is the term used when one or more natural enemies from the country of origin of the pest are identified, and one or more are imported and released to control the pest. The biocontrol agent is expected to establish permanently to reproduce and spread.

Natural enemies are one of the primary drivers determining the abundance and fitness of a species within an ecosystem. When an exotic plant or animal becomes established in a new and/or relatively simple ecosystem without its co-evolved natural enemies, it often reaches higher populations or has more vigorous growth than in its country of origin. As a geographically-isolated island nation with a temperate maritime climate, New Zealand has been able to exploit this ecological opportunity resulting in a robust economy based on agricultural, forestry and horticultural export industries heavily dependent on exotic plant and animal species. However, the resultant relatively simple productive systems are themselves susceptible to invasive exotic weeds and invertebrates. However, just as these invasive species may thrive and reach pest status through the absence of natural enemies and little competition, so can many introduced biocontrol agents. These too have performed well beyond expectation and allow New Zealand to export successfully high quality produce into internationally competitive markets under tight quarantine and pesticide residue restrictions.

New Zealand uses biocontrol to reduce greatly the need to use pesticides, provide cheap, long-term, self-sustaining control of pests, to conserve natural habitats and to foster sustainable systems dependent on natural processes with minimal intervention. It is a key component in integrated pest management programmes (IPM) in some of our largest export crops such as kiwifruit and pipfruit. The biocontrol agents themselves may be self-introduced or intentionally through classical biocontrol. For example, it was estimated that 92 species of natural enemies found in fruit crops in 1998 had established accidentally, compared with 24 through classical biocontrol introductions (Charles 1998).

The BCANZ (Biological Control Agents introduced to New Zealand) database (Ferguson et al. 2007) contains information on all biocontrol agents that have been purposely introduced to New Zealand to help manage weed and invertebrate pests. As at May 2010, the database contained records for 720 introductions of 518 biological control agents against 126 targets (25 weeds and 101 invertebrates). Fig. 2.1 shows the pattern of those introductions, starting with the introduction of the 11-spotted ladybird *Coccinella undecimpunctata* in 1874. Biocontrol expanded in the 1920s with introductions against blowflies and woolly apple aphid and peaked in the 1960s following the formation of a biocontrol group in Entomology Division of DSIR (Cameron et al. 1989). Introductions have decreased steadily subsequently. Partially this is because of growing awareness of risks to non-target organisms. In addition, the changing research environment, and associated flow on effects on resources and people, has led to more focus in all areas of biocontrol research from which pests or weeds are targeted to the optimisation of existing biocontrol in IPM systems. Furthermore, the introduction of the Hazardous Substances and New Organisms Act (HSNO) in 1998, implemented by the Environmental Risk Management Authority (ERMA New Zealand) has brought with it a cost to applicants for making an application to introduce new biological control agents.
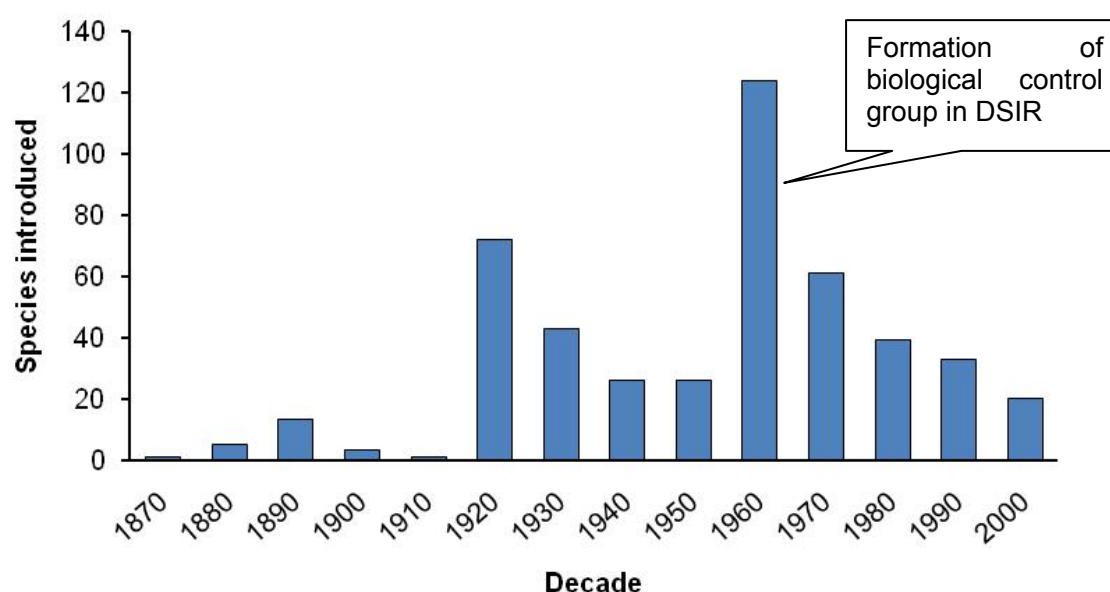

Figure 2.1: Number of species introduced into New Zealand for biocontrol by decade from 1870 to 2009 inclusive (Data from BCANZ database).

New Zealand has several features which make it a challenging environment for biocontrol (Waage 1997).
- A high level of international trade, with needs to avoid alien pests and maintain high quality in export produce.

- A highly unique flora and fauna with associated concerns for management of alien invasive pests and ecological effects of biocontrol introductions.
- A substantial number of important indigenous pests (e.g. grass grub, porina, leafrollers) that attack introduced plants and animals.

Stimulated by these challenges New Zealand has generated a substantial depth of research into biocontrol (including the development of local biocontrol products) and the systems within which they operate and has an unrivalled involvement of industry and public in both financing and making decisions about biocontrol agents (Waage 1997).

2.2 Climate change scenarios

The recommendations arising from this report are written for those involved in the long-term management of weeds and pests in production and indigenous ecosystems. Therefore the climate change scenarios used in this study have been aligned with the same time period projections as in the Guidance Manual published by the Ministry for the Environment for local governments (MFE 2008). The data used for all analyses in this report had the following characteristics:

- *Projected years*: current 1990 (average observed from 1980 to 1999); 2040 (average projection for 2030 to 2049); 2090 (average projection for 2080 to 2099).
- *Carbon emission scenarios*: 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPPC), scenarios A1B (medium emissions) and A2 (high emissions).
- *Global climate models* (GCMs): NIWA has assessed many GCMs and identified the twelve that work best for New Zealand, based on validation against the observed climates of the 20th century. These twelve GCMs are assumed to give the best predictions for NZ's future climates. We used the average of the predictions from these GCMs.
- *Climate variables*: mean monthly temperature expressed as a mean anomaly from the base period (1990 average of 1980 to 1999); mean monthly rainfall as a percentage of that of the base period. Relative humidity under future climates is likely to be very similar to current values, though absolute humidity may differ (Andrew Tait, pers comm).
- *Spatial resolution*: large-scale model predictions were down-scaled to a 5 km resolution grid based on the NZGD projection. This resulted in data for 11472 locations throughout the three main islands of New Zealand.

The results for the 12-model average A1B scenario are summarised in Figure 2.2, showing the projected changes over New Zealand in annual mean temperatures and rainfall in percent relative to 1990 for 2040 and 2090. The best estimates are for temperatures to increase by about 1°C by 2040, and 2°C by 2090, with the changes most pronounced in the north of the South Island, and most of the North Island. Westerlies are projected to increase in winter and spring and decrease in summer and autumn, resulting in changes in local rainfall patterns. For 2040 these ranged from an increase of 7.5 percent (West Coast of the South Island) to a decrease of 5 percent (along a thin coastal strip from Kaikoura north to East Cape, and in Northland). For 2090 the projected changes in precipitation range from an increase of over 10 percent (West Coast of the South Island) to a decrease of 7.5 percent (in patches along the coastal strip from Kaikoura north to East Cape, and in Northland).
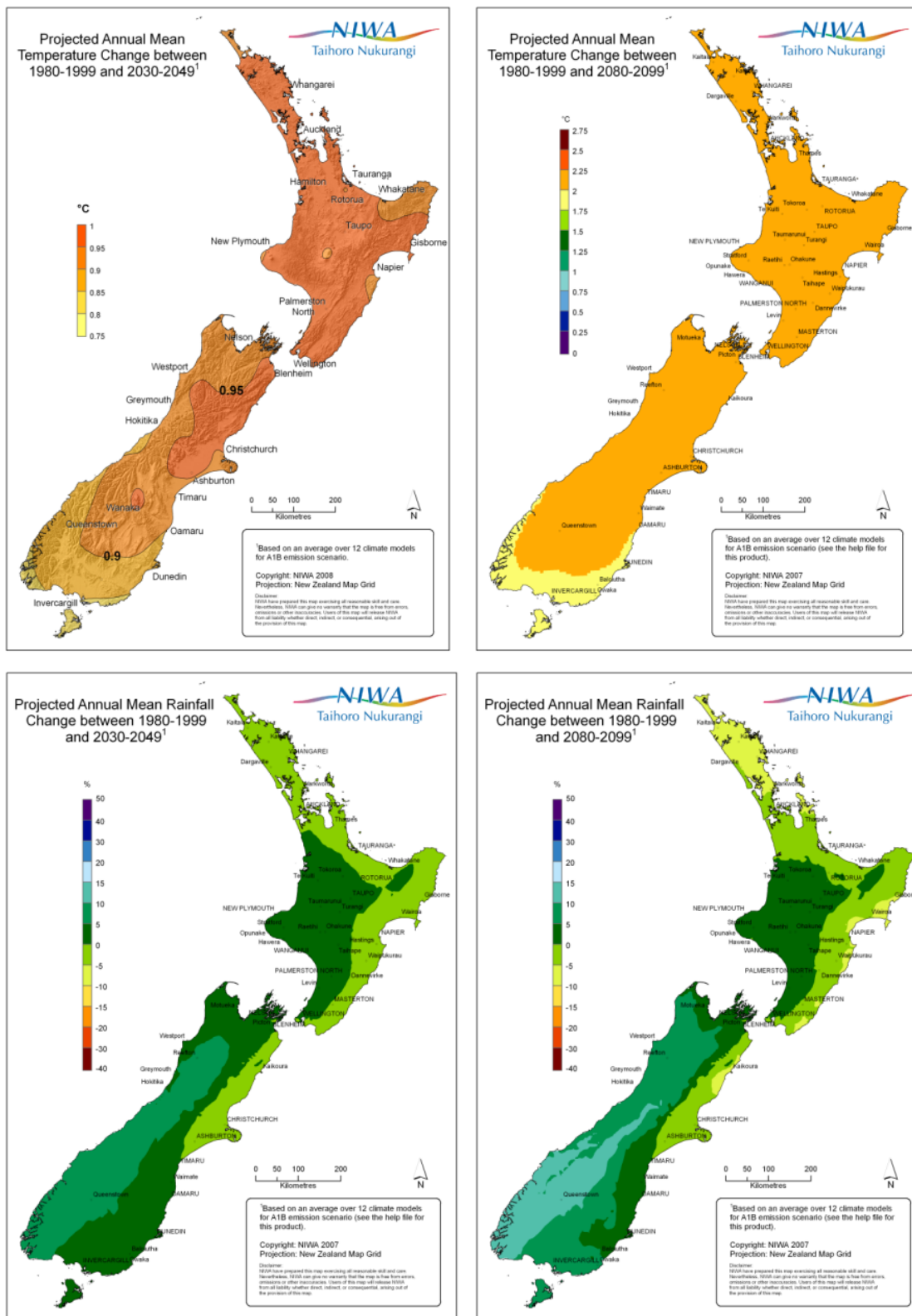
Figure 2.2: Projected changes in annual mean temperature (in °C) and in annual mean rainfall (in %), relative to 1990 assuming a moderate emissions scenario. Note the different temperature scales for 2040 and 2090. Results provided by NIWA.

3.   New Zealand biocontrol systems

Cameron et al. (1989) undertook a comprehensive review of the species introduced into New Zealand for the biocontrol of weeds and invertebrate pests between 1874 and 1987. A total of 321 species were introduced. Of these 225 were released and 70 became established as biocontrol agents. These introductions were targeted at 70 pests and Cameron et al. (1989) deemed impacts had been reported for 24 of these target species.

The Cameron et al. (1989) review of the successfully established biocontrol agents is summarised by sector and updated with subsequent introductions listed on the Landcare (www.landcareresearch.co.nz/research/biocons/weeds/) and BCANZ (Ferguson et al. 2007) web sites. A number of invertebrate pests and many weeds are found across sectors. Therefore the weed systems are listed separately and the pest system in the sector where control is most critical.

3.1   Pasture and forage invertebrate pests

Based on the Land Cover Database 2 (MFE 2004), 39 per cent of New Zealand's land cover is high-producing and low-producing grassland and production from these pastures is responsible for about $19,861 million of New Zealand's 2009 export earnings.

The introduced grasses, clovers and other pastoral forages such as lucerne are attacked by a range of notable pests (Table 3.1). Animal parasites that have part of their life cycle in pasture are also part of the pastoral ecosystem. Biocontrol is a highly applicable pest management tool in pasture and perennial forage crops such as lucerne as little or no insecticides are used because of cost, the risk of residues, growing reluctance by farmers to use pesticides, and because cosmetic damage is not an issue.

The native grass grub and porina have adapted well to the introduction of exotic pasture species. Although attempts to introduce exotic parasitoids to control these species failed (termed neo-classical biocontrol), success has been achieved with native pathogens associated with grass grub. A number of bacterial, fungal and protozoan pathogens including *Bacillus papillae* (milky disease) and *Serratia entomophila* (amber disease) provide natural control of grass grub larvae.

Knowledge that grass grub population outbreaks occur when inoculum levels in the soil are depressed following cultivation and collapse once disease levels increase has led to the development of *S. entomophila* as a biopesticide (Jackson 1989) and changes in on-farm decisions on pasture renovation methods (direct drilling vs full cultivation) and use of conventional pesticides.

The exotic pasture and forage insects that have been the target of biocontrol programmes are Argentine stem weevil, clover root weevil, lucerne weevil, black beetle, clover flea*,* and whitefringed weevil (Table 3.1). Success has been achieved only with the first three weevil species.

Several parasitoids were introduced to control blowflies with three species becoming established, alongside the indigenous *Aphaereta aotea*. In the field the parasitism rate on fly struck sheep is relatively low, possibly due to the difficulty parasitoids have in locating mobile struck sheep (Bishop et al. 1996). However up to 50% of maggots found on carrion, an important source of strike flies on-farm, can be parasitised (Cole & Heath 1999).

Table 3.1: Major pasture-based pests affecting the pastoral industry, their natural enemies and natural enemy source (N native; C classical biocontrol introduction; S self-introduced) and first release year.

Species	Natural enemy	Source
Indigenous pasture pests		
Costelytra zealandica, grass grub	*Bacillus papillae*	N
	Serratia entomophila	N
Wiseana spp Porina.	*Pterocormus lotatorius*	N
	Ctenophorocera usitata	N
	Hexamera alcis	N
	Diplocytis oxycani	N
	Metarrhizium anisopliae	N
Irenimus aequalis	*Microctonus zealandicus*	N
Exotic pasture pests		
Listronotus bonariensis, Argentine stem weevil	*Microctonus hyperodae*	C (1991)
Nematodes	Nematophagous fungi	S
Heterodera trifolii clover cyst nematode		
Meloidogyne hapla root-knot nematode		
Ditylenchus dipsaci stem nematode		
Pratylenchus spp.		
*Sitona lepidus ,*clover root weevil	Irish *Microctonus aethiopoides*	C (2006)
Heteronychus arator, black beetle	*Adelina tenebrionis*	S
	neoaplectanid nematode	S
	Beauveria sp.	S
	RNA virus	S
Teleogryllus commodus, black field cricket	cricket paralysis virus	S
Sminthurus viridis, clover flea	Generalist predators, e.g. *Bdellodes lapidaria*, spiders	S
Aphodius tasmaniae Tasmanian grass grub	unknown	
Graphognathus leucoloma whitefringed weevil	Generalist predators only e.g. *Conoderus exsul,* birds	S
Balanococcus poae pasture mealy bug	*Odiaglyptus biformis*	S
Aploneura lentisci root aphid	unknown	S
Adoryphorus couloni red headed cockchafer	Protosoan (possibly *Vavraia oncoerae*)	S
Herpetogramma licassarlis tropical grass webworm	Generalist parasitoids e.g. wasp, *Meteorus pulchricornis, Lissopimpla excelsa*	S
Deroceras spp. Field slugs	Generalist predators e.g. carabids *Holcaspis angustula, Megadromus antarcticus* and *Laemostenus complanatus*)	S
Exotic forage pests		
Acyrthosiphon kondoi bluegreen lucerne aphid	*Aphidius ervi, A. eadyi*	C (1977)
A. pisum pea aphid	*A. eadyi*	C (1977)
Sitona discoideus, lucerne weevil	Moroccan *Microctonus aethiopoides*	C (1982)
Plutella xylostella, diamondback moth	*Diadegma semiclausum*	C (1936)
	Diadromus collaris	C (1938)
	Zoophthora radicans	S

Nysius huttoni wheat bug
Animal parasites

Calliphidae, Blowflies	*Aphaereta aotea*	S
	Alysia manducator	C (1926)
	Tachinaephagus zealandicus	N
Animal nematodes	*Duddingtonia flagrans*	S
	Harposporium helicoides	S

3.2 Field and vegetable pests

This sector is tremendously diverse with around 50-60 crops being grown in any year affected by over 150 pests. Integrated pest management (IPM) programmes are available for many crops. The dominant pest species and associated natural enemies are given in Table 3.2. Onions (46%) and squash (25%) dominate the vegetable export market.

Table 3.2: Major invertebrate pests affecting field and vegetable crops, their natural enemies and natural enemy source (N native; C classical biocontrol introduction; S self-introduced).

Species	Natural enemy	Source (year)
Indigenous pests		
Chrysodeixis eriosoma green looper	Trichogrammid spp.	N
	Microgaster sp.	N
	Apanteles ruficrus	N, C (1970)
	Copidosoma floridanum	C (1969)
Agrotis ipsilon, greasy cutworm	Native tachinids	N
	Apanteles ruficrus	N
Exotic pests (excluding those already covered under forage crops)		
Agromyzidae, leaf miners e.g.	*Chrsocharis pubicornis*	S, C (1969)
Scaptomyza flava European leaf miner	*Hemiptarsenus varicornis*	S, C (1970)
	Asobara persimilis	S
Aphididae e.g. *Metopolophium dirhodum*, rose-grain aphid; *Macrosiphum euphorbiae*, potato aphid; *Myzus persicae,* green peach aphid; *Brevicoryne brassicae,* grey cabbage aphid; *Metopolophium dirhodum* rose-grain aphid.	*Aphidius rhopalosiphi*	C (1985)
	Diaeretiella rapae	S
	Aphidius ervi,	C (1977)
	A. eadyi	C (1977)
	Coccinella undecimpunctata	C (1874)
Nezara viridula, green vegetable bug	*Asolcus basalis*	C (?)
Thysanoplusia orichalcea, Soybean looper	Pakistan *A. ruficus*	C (1970)
	Copidosoma floridanum	C (1969)
	Meteorus pulchricornis	S
Mythimna separata, cosmopolitan armyworm	Pakistan *A. ruficus*	C (1970)
Phthorimaea opercula, potato tuber moth	*Apanteles subandinus*	C (1966)
Helicoverpa armigera (tomato fruit worm)	*Apanteles kazak*	C (1978)
	Microplitis croceipes	C (?)
	Meteorus pulchricornis	S
Pieris rapae, white butterfly	*Pteromalus puparum*	C (1933)
	Cotesia rubecula	C (1993)
	Apanteles glomeratus,	C (1931)
	A granulosis virus	S
Mayetiola destructor, hessian fly	*Platygaster hiemalis*	S
	Pediobius acantha	C (1893?)
	Aprostocetus zosimus	S
	Macroneura vesicularis	S
Bactericera cockerelli, tomato potato psyllid	-	
Heliothrips haemorrhoidalis, greenhouse thrips	*Thripobius semiluteus*	C (2001)
Trialeurodes vaporarium Greenhouse whitefly	*Encarsia formosa*	C (1933)

Nematodes e.g. *Globodera pallida* and *G. rostochiensis* potato cyst nematodes	-	

3.3 Fruit crop pests

Biocontrol programmes in fruit crops have been predominantly export led, firstly pip fruit (exports worth $363M in 2009) then kiwifruit ($987M 2009) and more recently the wine industry ($940M 2009). Summerfruit are also important exports ($241M 2009) while citrus is largely grown for the home market. Other export crops include avocado, berryfruit (blackberry, blackcurrant, blueberry, boysenberry, raspberry and strawberry) feijoa, nashi, persimmon and tamarillo.

The history of the establishment of fruit crop pests and their natural enemies was collated by (Charles 1998). Fruit crops in New Zealand are attacked by around 120 invertebrate pests, which is relatively few compared to other countries. Most are exotic but as broad spectrum pesticides are phased out, additional native species may gain pest status. These pests in turn are attacked by at least 135 arthropod natural enemies. The major pest and natural enemy species are presented in Table 3.3. Most are exotic and have established accidentally, with only 25 natural enemies established through classical biocontrol introductions (Ferguson et al. 2007).

The value of combining the use of selective pesticides while retaining natural enemies in integrated pest management (IPM) has been clearly demonstrated in New Zealand orchards since the late 1960s. Nowadays, biocontrol is the preferred pest management method within Integrated Fruit Production (IFM) and organic crop management systems. These are now the norm for apples, kiwifruit and wine-grapes, and similar programmes are being increasingly introduced to other crops.

Table 3.3: Major invertebrate pests affecting orchards, their natural enemies and natural enemy source (N native; C classical biocontrol introduction; S self-introduced).

Species	Natural enemy	source
Tortricid leafrollers		
Epiphyas postvittana, *Ctenopseutis obliquana*, *Planotortrix octo*, *Cnephasia jactatana*	Trichogrammatids	S, C
	Apanteles subandinus	C (1966)
	Xanthopimpla rhopaloceros	C (1967)
	Glyptapanteles demeter	N
	Dolichogenidea tasmanica	S
	Trigonospila brevifacies,	C (1967)
Cydia pomonella, codling moth,	*Ascogaster quadridentata*	C (1931)
Grapholita molesta, oriental fruit moth	*Glabridorsum stokesii*	C (1967)
Dasineura pyri & *D. mali*. Leafcurling midges	*Platygaster demades*	C (1925)
Edwardsiana froggatti Froggatt's apple leafhopper	*Anagrus spp*	S
Eriosoma lanigerum, Woolly apple aphid	*Aphelinus mali*	C (1921)
Icerya purchasi, Cottony cushion scale	*Cryptochetum iceryae*	C (1888)
	Rodolia cardinalis	C (1891)
Mites:		
Panonychus ulmi, European red mite	predatory mites (e.g	
Tetranychus urticae, two-spotted mite	*Phytoseiulus persimilis*,	C (1967)
Panonychus citri Citrus red mite	*Typhlodromus pyri*	S
	Neoseiulus fallacis),	C (1973)
	ladybirds	N
Pseudococcidae: mealy bugs	*Coccophagous gurneyi*	S

	Tetracnemoidea brevicornis	S
	Pseudaphycus maculipennis	C (2001)
Scolypopa australis, passionvine hopper	*Centrodora scolypopae*	S
	Ablerus sp.	S
Heliothrips haemorrhodalis Greenhouse thrips	*Thripobius semiluteus*	C (2001)
Megalurothrips kellyanus Kelly's citrus thrips	*Megaphragma* spp.	S
	Anystis baccarum	S
Diaspididae armoured scale	*Forficula auricularia,*	S
	Encarsia citrina,	S
	Hemisarcoptes coccophagus	C(1994)
	Signiphora spp.	S
	Aphytis spp.	S
Ceroplastinae wax scale	*Halmus chalybeus,*	N
	Euxanthbellus philippiae	S

3.4   Forestry

Exotic forests cover around 1.8 million ha of New Zealand and are predominately *Pinus radiata* (89%). However, while a minor component *Eucalyptus* spp. are important as they are the only fast grown plantation hardwood which could fill the $300 million demand for hardwood pulp and wood per annum. The forestry industry was worth $3207M in exports in 2009 (MAF 2010).

In addition to major plantation forestry, the forest industry is also considered to include the valuable and active farm forestry industry, mixed species woodlot and shelterbelt plantings, city and park street and amenity trees. These additional types of plantings hold significant value for New Zealand not just for specialty hardwood timbers for such end-uses as veneer, furniture and flooring, but also for the growing areas of carbon credits, lakes water quality programmes, ground-durable timber posts, bioenergy fuels, land stabilisation, human and animal shelter, sewage treatment schemes, and firewood.

Successful biocontrol of Sirex wood wasp enables *P. radiata* to be grown relatively pest free, with more recent biocontrol agent introductions being against *Eucalyptus* pests (Table 3.4).

Table 3.4: Major invertebrate pests affecting forestry, their natural enemies and natural enemy source (N native; C classical biocontrol introduction; S self-introduced) and year of introduction.

Species	Natural enemy	Source
Pinus radiata		
Sirex noctilio, wood wasp	*Deladenus siricidicola*	S
	Megarhyssa nortoni	C (1964)
	Ibalia leucospoides	C (1966)
Hylastes ater , bark beetle	*Metarhizium flavoviride var. pemphigi*	S
	Hirsutella guignardii	S
Eucalyptus spp.		
Opodiphthera eucalypti, emperor gum moth	polyhedral virus	S
Paropsis charybdis, eucalyptus tortoise beetle	*Enoggera nassaui*	C (1987)
	Neopolycystus insectifurax	C (1987)
Gonipterus scutellatus, snout weevil	*Anaphes nitens*	C (1927)
Phylacteophaga froggatti, eucalyptus leaf-blister sawfly	*Bracon phylacteophagus*	C (1988)
Ctenarytaina eucalypti blue gum psyllid	*Psyllaephagus pilosus*	S
Glycaspis brimblecombei, red gum psyllid	*Psyllaephagus bliteus*	S
Gum-tree Scale *Eriococcus coriaceus*	*Rhysobius ventralis*	S
	Stathmopoda melanochra	C (1932)
Cardiaspina fiscella, Brown lace lerp	*Psyllaephagus gemitus*	S
Uraba lugens, gum leaf skeletoniser	*Cotesia urabae*	C (2010)
Strepsicrates macropetana, eucalyptus leafroller	*Trigonospila brevifaces*	C (1967)
Acacia		
Dicranosterna semipunctata, Acacia tortoise beetle	*Cleobora mellyi*	C (1979)
	Neopolycystus sp. Rotorua	S
Acizzia acaciae, A. uncatoides and A. albizziae, acacia psyllids	Ladybirds	S
	Psylla acaciae	

| *Acrocercops alysidota*, acacia leaf miner | *Cirrospilus* sp. | S |
| | *Diaulohorpha* sp | S |

3.5 Weeds

Weeds grow in all sectors, from lowland pastures and horticultural crops to high country tussock grasslands and indigenous forests. Weed biocontrol is a particularly useful tool in extensive systems such as forestry, pastoral farming and the indigenous estate where there is no immediate need to kill every plant to prevent economic losses. Biocontrol is often the only option that can be used in these systems because other means are not physical or economically possible or pose unacceptable risks to the environment. The successful weed biocontrol programmes are listed below under the sector (productive or natural environment) that has been the primary target for their biocontrol (Table 3.5) and includes two rusts (*Puccinia* spp.), one of which (*P. hieracii var. piloselloidarum*) may have been introduced illegally (McKenzie 1998). A full list is available at http://www.landcareresearch.co.nz/research/biocons/weeds/. Native natural enemies have mostly very minor effects on weeds and are not listed.

Table 3.5: Major classical biocontrol agents introduced and established for weeds. The year of first release is shown for deliberately released biocontrol agents.

Species	Natural enemy	Source (year)
Productive sectors		
Buddleja davidii Buddleja	*Cleopus japonicus*	C (2006)
Carduus nutans Nodding thistle	*Rhinocyllus conicus,*	C (1973)
	Trichosirocalus horridus,	C (1979)
	Urophora solstitialis	C (1990)
Cirsium arvense Californian thistle	*Cassida rubiginosa* (new),	C (2007)*
	Ceratapion onopordi (new),	C (2008)*
	Lema cyanella	C (1983)
	Urophora cardui	C (1994)
Cirsium vulgare Scotch thistle	*Urophora stylata*	C (1999)
Cytisus scoparius Broom	*Aceria genistae*	C (2008)
	Arytainilla spartiophila,	C (1993)
	Bruchidius villosus,	C (1987)
	Agonopterix assimilella	C (2008)
	Gonioctena olivacea	C (2008)
	Leucoptera spartifoliella	S
Hieraciumpilosella Hawkweed	*Aulacidea subterminalis,*	C (1999)
	Macrolabis pilosellae,	C (2002)
	Puccinia hieracii var. piloselloidarum	S + C (?)[+]
Hypericum perforatum St John's wort	*Chrysolina hyperici*	C (1943)
	C, quadrigemina	C (1963)
	Zeuxidiplosis giardii	C (1961)
Jacobea vulgaris Ragwort	*Botanophila jacobaeae*	C (1936)
	Cochylis atricapitana	C (2009?)*
	Longitarsus jacobaeae,	C (1983)
	Platyptilia isodactyla	C (2009?)*
	Tyria jacobaeae	C (1929)
Rubus fruticosus Blackberry	*Phragmidium violaceum*	S
Ulex europaeus Gorse	*Agonopterix uumbellana,*	C (1990)
	Cydia ulicetana,	C (1992)
	Exapion ulicis,	C (1931)
	Pempelia genistella	C (1998)
	Sericothrips staphylinus,	C (1990)
	Tetranychus lintearius	C (1989)
Natural environment		

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Ageratina adenophora Mexican Devil weed	*Procecidochares utilis*	C (1958)
Ageratina riparia mist flower	*Entyloma ageratinae*	C (1998)
	Procecidochares alani	C (2001)
Alternanthera philoxeroides Alligator weed	*Arcola malloi,*	C (1982)
	Agasicles hygrophila	C (1982)
Asparagus asparagoides	*Puccinia myrsiphylli*	S
Chrysanthemoides monilifera Boneseed	*Tortrix* s.l. sp. "*chrysanthemoides*"	C (2007)
Calluna vulgaris Heather	*Lochmaea suturalis*	C (1996)
Clematis vitalba Old man's beard	*Phoma clematidina*	C (1996)
	Phytomyza vitalbae	C (1995)

Key: C classical biocontrol introduction; S self-introduced
[+]Two additional strains released once species found on weed in New Zealand
* Too recent to confirm establishment or not

3.6 Cultural and quality of life

Invertebrate parasitoids and predators impact on species that may not be of high economic status but are important to New Zealand communities. These include beneficial species that help protect iconic native plants and crops of particular significant to Maori. Conversely, some introduced parasitoids have deleterious effect on valued insect species.

Table 3.6: Examples of natural enemies with cultural or quality of life significance

Pest or valued species	Natural enemy	Source
Natural environment/nuisance		
Vespula spp. wasps	*Sphecophaga vesparum vesparum*	C (1985)
Maori crops		
Spodoptera litura tropical armyworm (kumara field crops)	*Meteorus pulchricornis*	S
Non-target impacts		
Danaus plexippus Monarch butterfly	*Miomantis caffra* African preying mantis	S
Vanessa gonerilla gonerilla Red admiral	*Echthromorpha intricatoria*	S
Pericoptus truncatus large sand scarab	*Radumeris tasmaniensis* yellow flower wasp	S
Amenity		
Phyllonorycter messaniella oak leaf miner	*Apanteles circumscriptus*	C (1957)
	Achrysocharoides splendens	C (1957)
Mycopsylla fici – Morton Bay Fig wasp	*Psyllaephagus cornwallensis*	S
Public health		
Muscid flies	*Muscidifurax raptor*	C (1969)
	Spalangia spp.	C (1969)

Many of the above biocontrol complexes in New Zealand were built up over the last century. It is evident from the literature that while there are 70 introduced and many more native and self-introduced biocontrol agents helping reduce the impact of weeds and pests, relatively few have been studied in depth. We do not have any measure of the current efficacy of many of the most common predators and parasitoids in our ecosystems, let alone sufficient information on them to predict future distribution and impact under climate change. It is also probable that many agents are soil-system and pathogen based and the impacts are unknown.

Climate change increases the risk of new pests establishing or "sleeper" pests emerging. It is a fact that there are many more species of insects in sub-tropical and tropical parts of the world, and more of these will be able to establish in those parts of New Zealand that become warmer. The absence of winter frosts in the northern North Island especially will allow establishment of some species and continual development throughout the year by others. Relatively common plant species currently not regarded as weeds (e.g. sorrel, acacias, and prairie grass) may become problematic in some regions. While the emergence of a new pest species may not directly appear a biocontrol issue, managing it in an existing IPM system would be a major challenge. There are not the resources available to develop new IPM systems quickly and the introduction of a new exotic natural enemy takes time – typically 10 years.

4.   Impacts of climate change on New Zealand biocontrol systems

Climate change is a worldwide concern which has generated considerable discussion and research into possible effects on agroecosystems (Fuhrer 2003). While increased levels of CO_2 are expected generally to increase plant productivity, negative impacts are predicted from reduced water availability, and for many crops, from higher temperatures. However, most of these studies were concentrated on individual species whereas biocontrol systems involve interactions between species at different trophic levels.

(Berg et al. 2010) acknowledged that the sheer number of potential interactions makes a full study of the impact of climate change on a community daunting. They analysed 50 years of published literature for two traits most likely to impact on a species dealing with climate change; thermal sensitivity and dispersal ability, and found pronounced and consistent differences among trophic groups. They found species living in habitats with relatively constant temperatures, such as in soil, have a weaker thermal response traits compared with above ground species, which live under more fluctuating regimes. There was little evidence for changes in the absolute climate tolerance of a species and herbivores respond more strongly to temperature than plant growth. They emphasised that temperature-induced changes could also result in a mismatch in phenologies that can have immediate and serious consequences.

A review of the diverse ways in which climate change is likely to influence natural enemies of agricultural pests has been recently published (Thomson et al. 2010). The review built on a previous review of the impact of temperature extremes on parasitoid interactions (Hance et al. 2006; Thomson et al. 2010). In this section we combine this and other international data with specific opinion and analysis of likely impacts of climate change on New Zealand biocontrol systems gathered from New Zealand biocontrol specialists who took part in a workshop in March 2010 (participants listed Section 10)
The aims of the workshop was to distil from the collective knowledge of the participants the probable impacts climate change will have on New Zealand biocontrol systems.

The consensus was that as climate changed, there is likely to be a fundamental change in the plants that grow in each zone. Most cropping systems will move southward and the biocontrol systems will move with them with little immediate change in composition and impact. This could pose particular challenges to Maori groups that do not always have a choice of moving their crops/land as other growers can. While economic factors could cause more rapid shifts (the wine and dairy industries are recent examples of large shifts in land use in the South Island), industry knowledge of the importance of natural enemies in production systems should ensure that they are transferred with the crop. Therefore, the focus was on those systems where climate change could make a difference, either positively or negatively.

The review is structured around four different levels at which climate change effects may manifest. The broadest scale is that of the geographic distributions of crops grown, the weeds and pests which attack them, and the biocontrol agents that may help mitigate the damage. Often, the geographic distributions of free-ranging species will be largely determined by processes of reproduction and mortality acting on individuals within local populations. These, in turn, may be determined by interactions with other species, especially with host plants, prey, competitors and natural enemies. At the finest scale, climate change may result in evolutionary changes in pest and natural enemy populations.

4.1 Species distributions

4.1.1 Geographic range shifts

The plant species produced in a region are expected to change over time with climate change as growers choose those crops and forages that optimise economic returns. As climate change is a gradual process it is predicted that most pests and their natural enemies will move with the host plants. Increased temperatures may be expected to extend poleward the range of species currently limited by low temperature and frosts, or increase the altitude at which they can survive. A 2°C rise in temperature is equivalent to a shift of current northern hemisphere conditions of 600 km latitude or 330 m in elevation (Parry 1989). This is equivalent to approximately 6 km per year latitude or 3.3 m per year elevation. Given that the environmental tolerances of insects demonstrate some level of plasticity it is considered that most insects would be capable of tracking such changes. However, some species, such as predatory mites, may have low dispersal rates. A further consideration is that the time taken for biocontrol systems to integrate into a new area will be influenced particularly by the supplementary resources needed (e.g. nectar and pollen, overwintering or aestivation sites). The patchwork of micro-ecosystems enabling reservoirs for biocontrol agents are important.

In New Zealand, most weeds are likely to expand or shrink their geographic ranges in response to changes in temperature (including lack of extremes such as frosts) and rainfall. As above, in most cases existing biocontrol agents are likely to track the changing distributions of their host plants. Geographical barriers are unlikely to be an issue for agent dispersal, with the exception of remote island systems. In the latter, there could be a need to move weed biocontrol agents should target weeds emerge as problems because of climate change. This seems simple enough, but usually does not take place – e.g. gorse has become a more serious weed on the Chatham Islands in recent decades (possibly due to increased pollination by honeybees) but no attempts have been made to increase the suite of gorse biocontrol agents established there.

The simplistic hypothesis that everything will move south is challenged also by the knowledge that there are disparities in the climate tolerances of hosts and their natural enemies. Existing disparities in current host: biocontrol agent distribution ranges may be accentuated or negated by climate change. Contributing to this is insect diapause and aestivation which allows populations to survive periods of adverse conditions. As diapause and aestivation in some species can be induced and maintained by photoperiod alone, while in others temperature plays a more important role (Tauber & Tauber 1976), a geographical shift in latitude may have marked impacts on host:parasitoid relationships. The butterfly *Pieris napi oleracea* has disappeared from Massachusetts but persists in Vermont because the northern populations enter diapause. With only one generation a year, it is not vulnerable to the introduced braconid parasitoid *Cotesia glomerata* (Benson et al. 2003).

The outcomes may be positive or negative for New Zealand biocontrol. Some examples where outcomes are likely to be beneficial are:

- The European leaf miner parasitoid (*Scaptomyza flava*; ex South Australia) is currently effective in the North Island but not the South Island.
- Alligator weed suppression by *Agasicles* is likely to improve because the agent's impact is thought to be reduced by cooler temperatures.

- The introduction of the St Johns Wort beetles, *Chrysolina* , represent the most successful weed biocontrol programme in New Zealand, with their target weed, *Hypericum perforatum*, eliminated or suppressed below weed status over almost all of its previous range. The small areas where suppression of *Hypericum perforatum* appears inadequate are in relatively high altitude pastures, particularly in the most southerly parts of its range e.g. in the Queenstown and Wanaka region. It is conceivable that increased temperatures from climate change could increase the effectiveness of the beetles in these regions.

Some negative outcomes may arise:
- The clover root weevil biocontrol agent (the Irish strain of the European biotype of *Microctonus aethiopoides*) originates from northern Irish counties, localities with quite widely differing photoperiod and temperatures than northern North Island. It was slow to establish and is poorer performing in the far north than elsewhere in New Zealand. Will the photoperiod /temperature interactions be accentuated by climate change?
- Expansion of the range of ragwort may endanger native *Senecio* spp. as both are hosts to the native magpie moth, *Nyctemera annulata*.
- Climate change could lead to increased use of lucerne in drought-prone regions. This would increase the abundance of Moroccan *Microctonus aethiopoides* in the environment, a species known to attack a range of native weevils.
- Altitude range of white clover and CRW might increase and take the Irish biotype into contact with more potential non-target hosts.

Climate change aiding Eucalyptus tortoise beetle biocontrol?

The Eucalyptus tortoise beetle (*Paropsis charybdis*) is a foliar feeder causing major damage to eucalypts in the subgenus Symphyomyrtus, in particular *Eucalyptus globulus* and *E. nitens*. Both are considered key in the development of a fast-rotation short-fibre pulp for high quality papermaking in New Zealand (Wilcox 1980) but the use of *E. nitens* for future carbon uses is limited by its susceptibility to the beetle.

Classical biocontrol of the pest was achieved in the late 1980s using the egg parasitoid *Enoggera nassaui* (Hymenoptera: Pteromalidae). This was generally successful except in cooler, high altitude regions. This partial failure was attributed to the original sourcing of the egg parasitoid from a frost-free area in Western Australia (Murphy 1998; Murphy & Kay 2000). A CLIMEX climate matching exercise showed that this locality was similar to only the upper north Island of New Zealand (Murphy 2006). Supporting this theory is a lower survival rate by the parasitoid in colder areas (Bain and Kay 1989) and a $3^{o}C$ higher temperature developmental threshold than its host (McGregor 1984; Mansfield et al. 2010).

The situation has become more complex with the arrival of two self-introduced species. A hyperparasitoid, *Baeoanusia albifunicle,* dominants *E. nassaui* late in the season (Nahrung & Duffy 2008). A second primary parasitoid, *Neopolycystus insectifurax*, with an even higher temperature threshold for development that the previous two species (10.0 ºC) (T. Withers, unpub. data), can be found from mid Canterbury northward (Murray et al. 2008b).

It would be promising for the Eucalyptus industry if under climate change, *N. insectifurax* could have a greater impact upon Eucalyptus tortoise beetle or if either egg parasitoid were better able to control their host population densities in the historically colder and higher altitude regions of New Zealand such as Southland and the Central North Island plateau. Major plantings of these plantations species are occurring in these regions.

4.1.2 New pest species

The major part of this review and analysis examines the potential effects of climate change on existing biocontrol systems. However, climate change is likely to make significant parts of the North Island hospitable to cold/frost sensitive subtropical species.

New Zealand's geographical isolation accentuates our greatest risk from climate change: that of colonisation by new invasive pest or the emergence of "sleeper pests". In most instances, novel invasive species arrive without their co-evolved natural enemies and those already present in the new region provide poor control. New Zealand, as a temperate island nation, has been exposed to airborne species from Australia for millions of years, but most frost-sensitive species have not established (Phillips et al. 2006). Added to this are the other 'door-knockers' arriving through human activities. However, with increasing temperatures and the probability of increased use of subtropical species in production systems, it is inevitable that establishment events are likely to increase in frequency. Without specific natural enemies, some will become pests.

"Sleeper pests" are those already in the country but kept in check by factors such as host unavailability and cold. Some existing plant species that are minor weeds, or even merely garden ornamentals, are likely to become priority weeds for management in New Zealand under future climate change scenarios. Minor insect pest species persisting in isolated microhabitats or regularly arriving by wind (e.g.tropical grass webworm *Herpetogramma licarsisalis*) will also increase in significance. The migratory locust *Locusta migratoria* is found in New Zealand, but because of existing temperatures, swarming behaviour is absent so the insect currently is not regarded a pest. On the positive side, some glasshouse biocontrols may be able to effect control in the field.

There may be value in predicting the potential impacts of these "sleeper pests", and considering pre-emptive action particularly if biocontrol has already been successful in other parts of the world. Such programmes can be relatively inexpensive to transfer to New Zealand.

The successful biological control of mist flower in New Zealand could be regarded as an example of this type of action (Barton et al. 2007). Although mist flower biocontrol was primarily undertaken because of threats to indigenous ecosystems, experience in Hawai'i showed it's potential as a pasture weed (Trujillo 1985). Future climate change scenarios would almost certainly have led to mist flower becoming an invasive pasture weed over a wide geographic range in New Zealand, a threat that has probably been mitigated by successful biocontrol. In cases where the potential for biocontrol of a weed appear poor e.g. because of lack of success elsewhere, then a high priority ought to be to develop alternative management plans based on good quality surveillance and local eradication/management. Of course, modelling the range changes in existing or new weeds in response to climate change scenarios can, in theory, be done rather easily (e.g. Watt et al. 2009), but there are some major limitations. For example, we seldom know the current geographic distribution of the weeds in New Zealand. Furthermore, we have an extremely poor understanding of, and hence ability to predict, rates of spread of weeds from current to future distributions.

4.2 Intraspecific population dynamics

4.2.1 Direct responses to changes in CO$_2$, temperature and water

Increased temperatures, CO$_2$ and changes in water availability are likely to affect the individual species in a biocontrol system differentially and they way they do will vary from system to system. With winters insufficiently cold to check insect reproductive activity, species like aphids and thrips will multiply and predators may not keep pace and control the population.

Contrasting outcomes have been observed in model aphid systems. The abundance of peach potato aphid *Myzus persicae* was enhanced by both elevated CO$_2$ and a temperature increase of 2°C, whereas parasitism rates by its parasitoid *Aphidius matricariae* remained unchanged in elevated CO$_2$ and only trended upwards in elevated temperature (Bezemer et al. 1998). These authors concluded *M. persicae,* an important pest of many crops, might increase its abundance under conditions of climate change. However, little change in aphid population dynamics was predicted under elevated CO$_2$ and temperature in the (Hoover & Newman 2004) model. In contrast, in a model system using the aphid *Sitobion avenae,* the predator *Harmonia axyridis* and the parasitoid *Aphidius picipes,* both predator and parasitoid increased attack rate in elevated CO$_2$ and as a consequence substantially suppressed aphid abundance (Chen et al. 2007).

Warmer temperatures are likely to alter invertebrate behaviour. "Sit and wait" spiders move to cooler niches in the habitat while active hunting species cover larger territories with resulting increased chance of negative predator-predator interactions (Barton & Schmitz 2009). This increased hunting activity may have flow-on effects. In a field food web, increased temperature intensified the behavioural shift by grasshoppers to feed preferentially on herbs rather than grasses in the presence of hunting spiders (Barton et al. 2009).

Temperature has a direct effect on the pathogenicity of fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* which can be either very virulent, causing extensive and rapid mortality in days, or virtually benign, with the same hosts surviving for weeks or even months (Thomas & Blanford 2003).

Temperature can have considerable effects on host susceptibility to parasitoids with fairly common observations that high temperatures can enhance survival of parasitized hosts (although whether this is due to increased encapsulation of the parasitoid larvae by the host, or greater direct mortality of the parasitoid owing to a higher thermal sensitivity, is often not determined) (Thomas & Blanford 2003).

Temperature has a direct effect on the maximum potential fecundity of *Microctonus hyperodae*, the Argentine stem weevil biocontrol agent (Phillips, unpublished)

4.2.2 Plant-mediated effects

Increases in CO$_2,$ changes in water availability and increases in temperature will alter plant penology, growth and distribution, all of which will have flow-on effects on the plant herbivores and those that prey on them.

Aspects of plant life cycle events controlled by temperature, such as the timing and duration of seed germination, bud burst, and flowering, are likely to change with warmer temperatures, subject to photoperiod and water availability. Similarly, herbivore and natural enemy activity may be extended at both ends of the season. The degree that individual species benefit will depend on how well the life cycle events are synchronised to ensure optimum survival.

Changes in host plant quality in response to elevated CO_2, drought or flooding may also cause shifts in herbivore and natural enemy fitness. In general, elevated CO_2 leads to a decrease in the nutritional value of plants. There is a tendency for foliage feeders to consume more plant material (greater damage), but to grow and develop more slowly, and have reduced fecundity and survival. A New Zealand example of this came from the FACE (Free-Air CO_2 Enrichment) trial at Palmerston North. Female clover root weevil adults fed clover leaves from high CO_2 plots (pasture at predicted 2080 CO_2 levels and altered temperatures) lost reproductive capability earlier than those fed leaves from normal C plots (Phillps, McNeill & Newton, unpublished). On the other hand, some phloem feeders were reported to have better survival. For instance, cotton is attacked by two aphids *Gossypium hirsutum*, and *Aphis gossypii,* which are in turn are attacked by the ladybird *Propylaea japonica*. Under elevated CO_2, cotton aphid survival significantly increased but ladybird larval development took significantly longer (Gao et al. 2009). Therefore, the aphids may become pests that are more serious in the future.

Increased rainfall reducing heather control

Recent research has highlighted extremely low organic nitrogen levels in heather, *Calluna vulgaris*, as one of the reasons why heather beetle, *Lochmaea suturalis*, performance has been poorer than expected on the Volcanic Plateau in central North Island. Low nitrogen levels in heather in these environments are thought to be linked to high rainfall leaching the volcanic soils. It is possible that the problem could get worse under climate change scenarios, perhaps increasing the zone where heather beetle performance has been poor.

Reductions in prey size and fitness are likely to have greatest effect on koinobiont parasitoids developing inside a single host as, in general, host quality is an important determinant of parasitoid fitness and fecundity. However, a decrease in prey size may lead to increased numbers of prey consumed by predators, leading to improved pest control. The omnivorous bug *Oechalia schellenbergii* performed best when feeding under elevated CO_2, because the larvae of polyphagous pest *Helicoverpa armigera* were smaller and more easily subdued than when in ambient air (Coll & Hughes 2008).

Increases in herbivore development time due to changes in plant quality through elevated CO_2 or moisture stress can extend the period of availability to predators and parasitoids. Moisture stress is implicated in reduced parasitism in the mealy bug *Phenacoccus herreni*. The immune response of these mealybugs is greater on water stressed plants, leading to 30-50% encapsulation rates for three parasitoids (Catatalud et al. 2002).

Changes in temperature and moisture stress can influence production of plant defence compounds against plant herbivores. It is known that levels of many insect-resistance allelochemicals increase during drought. However, herbivore detoxification systems and immuno-competence may also be enhanced (Mattson & Haack 1987) and there can be flow-on effects to parasitoids (Kauffman & Kennedy 1989).

Weed biocontrol agents often depend on volatile organic compounds to locate host plants and herbivore attack often induces plants to release specific volatiles that alert parasitoids to the presence of potential hosts (Micha et al. 2000). Even small changes in climatic conditions can alter the intensity and rate of release of volatiles. Each parasitoid is likely to have its own optimal temperatures for signal perception; thus extreme

temperatures or large fluctuations can strongly affect the capacity of biocontrol agents to locate hosts and host habitats (Hance et al. 2006 and references therein).

Even the simple change in plant biomass through greater productivity or longer growth season will affect biocontrol systems. In New Zealand, increased temperatures will increase kikuyu growth and distribution. Whether this is regarded as a weed or useful plant depends on farmer system/perspective. Kikuyu is susceptible to tropical grass webworm and with increased growth and the increased likelihood of the formation of dense stoloniferous mats, the pest may "escape" from biocontrol.

4.2.2 Climate variability

Most biocontrol systems perform best under a stable environment. However, in addition to the forecast increase in mean temperatures, CO_2 and shifts in rainfall distribution (section 2.2), climate variability is expected to increase. Extreme weather events such as droughts, flood and even unseasonal frosts are predicted to occur more frequently. While many species have mechanisms to cope with extremes, they require time to acclimatize and/or enter the resistant state. The relative vulnerability of the host plants, pests and biocontrol agents to extremes of temperature, desiccation or flooding will determine whether the drought or flood will be followed by a weed or pest outbreak.

Exposure to temperature extremes induces lethal and sub-lethal damage to parasitoids (Hance et al. 2006). It generally decreases longevity, fecundity, mobility, the ability to orient themselves toward attractive odours, and learning capacities. It can even result in the production of more males. The *Wolbachia* bacterial endosymbionts that facilitate parthenogenesis can be eliminated by short exposure to high temperature (Thomas & S. 2003).

Extreme weather events such as drought are followed frequently by pest population explosions because of the loss of natural enemies. Field data indicate that parasitoids are generally more sensitive than their hosts, and lag behind in population recovery (Thomson et al. 2010 and references therein). This has been reported in diverse habitats. Extremely hot dry weather in Slovakia in late spring 1993 resulted in no egg parasitism of European corn borer in crops (Cagan et al. 1998). In Pennsylvania, galls of *Eurosta solidaginis* are parasitized by three *Eurytoma* spp. wasps and drought was shown to drastically reduce these wasps with slow subsequent recoveries to pre-drought numbers (Sumerford et al. 2000).Outbreaks of foliar feeders were seen in rain forest following a severe drought in Borneo in 1998 (Harrison 2001). The frequency and severity of droughts has increased substantially in Borneo in recent decades, and climate models suggest this may be the result of global warming. Therefore regions that have the likelihood of increased frequency and severity of droughts may not be able to depend solely on biocontrol as a pest management method in either environmental or production sectors.

Generally the host is more resistant to extremes in climatic variability/events than natural enemy. Therefore after local extinctions due to an extreme climatic event, the pest reintroduces more rapidly than the biocontrol agent.

New Zealand examples of vulnerable systems include:
- *Hieracium* spp. biocontrols do not do well in summer droughts. This weed is already in an extreme environment and the increased rainfall predicted for inland South Island areas may benefit the biocontrol agents.
- Heather beetle *Lochmaea suturalis* can handle extreme fluctuations in temperature but not as many frosts as the host.
- Alligator weed withstands flood better than the biocontrol agent.

Grass grub/ drought/ pathogens

Grass grub outbreaks often occur two to four years after a severe drought (East & Willoughby 1980). Both *Bacillus papillae* (milky disease) and *Serratia entomophila* (amber disease, Fig. 4.2.1) have limited survival in dry soils and summer droughts (East & Wigley 1985; O'Callaghan et al. 1989) but this would not have a major effect as long as diseased grass grub larvae are present from the previous generation. However, during droughts a combination of desiccation, exposure to high temperatures and starvation reduces both diseased and healthy larval populations to low densities, resulting in low infection rates in the next couple of generations. Therefore, increased frequency of droughts is likely to lead to more unstable populations and damage outbreaks. Conversely, the combination of higher temperatures and increased rainfall in much of the central and west coast regions of the North Island and all but the mid and upper eastern regions of the South Island may improve grass grub control by pathogens. Higher temperatures and moist soil conditions are likely to accelerate disease development and lead to an increase in the level of natural population regulation of grass grub (Prestige 1990).

Figure 4.2.1: Healthy (left) and *Serratia entomophila*-infected (right) grass grub larvae.

One distinctive characteristic of New Zealand's landscape is that it has many microhabitats that can act as refuges. This will provide a buffer against any catastrophic effect of a major weather event and will help prevent widespread extinction of biocontrol systems operating in a region.

4.3   Interspecific population interactions

Natural enemies with very narrow and specific host ranges, a highly desirable attribute for classical biocontrol programmes, may be more sensitive to climate change than generalist herbivores and predators. The interactions between plants, herbivorous

insects, and parasitoids result from a long co-evolution in a particular environment. Parasitoids are more likely to be affected by climate change than plant herbivores because they depend on the capacity of the lower trophic levels to adapt to these changes. Those that kill their hosts only when their development is completed (koinobiont) are particularly vulnerable, as their hosts must remain alive throughout their development. They rely on and may influence the behaviour of the parasitised host so that it seeks locations where survival is more probable.

Diapause and aestivation are a means of surviving climatic extremes and are frequently induced by changes in day length and temperature extremes. In parasitoids, diapause often takes place in the host or in the host mummy and is thus influenced by host conditions. In some koinobionts it is the host hormones that control the suspension of development (e.g. *Microctonus aethiopoides* in the lucerne weevil *Sitona discoideus* (Goldson et al. 1990) thus ensuring the parasitoid aestivation or diapause period is strictly sympathetic with the host.

4.3.1 Generation time ratio

Population dynamics theory predicts that the extent to which a predator population suppresses its prey population is determined by the ratio of the predator's generation time to that of its prey (Godfray & Hassell 1987, Kindlmann & Dixon 1999a, b). When the generation time ratio (GTR) is low, then a predator population can increase rapidly compared to its prey, and greater suppression is possible. While the GTR has been shown to be a strong predictor of prey suppression by predators (Kindlmann & Dixon 1999a, b), the theory has also been applied to parasitoid-host systems (Mills 2006) and to explain the success or failure of some classical biological control introductions to New Zealand (Barlow et al. 2002).

Low GTR => potentially effective biocontrol
High GTR => potentially ineffective biocontrol

The number of generations that an insect population can complete each year is primarily determined by its diapause cues (e.g. photoperiod) and temperature-dependent development rates. When these differ between a pest and its natural enemies, then the GTR, and consequently the level of pest suppression, is expected to vary with climate. Therefore, the GTR is a useful tool for assessing potential changes in biocontrol systems because of climate change.

Climate change may influence the GTR of biocontrol systems in several ways. First, insects generally have a minimum temperature required for development, and this development threshold can differ between biocontrol agents and their hosts. When the threshold is lower in the host than in the enemy, then pest suppression should increase with warming (i.e. GTR declines). If the thermal development threshold is higher in the host than in the enemy, then warming may reduce pest suppression (i.e. GTR increases). When the threshold is similar for both species, then warming alone is unlikely to affect pest suppression.

On an annual basis, the GTR is also affected by any diapause or aestivation experienced by the pest or natural enemy. If natural enemies diapause whereas their hosts do not, then the GTR will be higher than otherwise, and the diapause period creates a temporal refuge from attack which may allow the host population to escape control by its enemies. Conversely, a lower GTR and greater suppression may result when natural enemies can continue to develop or reproduce while their hosts are diapausing. Since the timing of diapause is primarily controlled by daylength in many species (de Wilde 1962), it is unlikely to change significantly under future climates, and the interaction between daylength and temperature is likely to be important for determining the effects of climate

change on biocontrol systems. Examples are given in the woolly apple aphid, lucerne weevil and Argentine stem weevil case studies.

In many cases the extrinsic factors controlling diapause are complex, often involving interactions between daylength, temperature, and other factors such as moisture, nutrition, crowding, and maternal effects. For example, autumn diapause induction in Australian *Helicoverpa* sp. may be modelled by a function of date and temperature (Dillon 1998). In addition, species diapause triggers may evolve in response to new climates, as they have in *Hyphantria cunea* populations invading southern Japan (Gomi 1997). Therefore, predictions of the effects of future climates on diapausing species are subject to considerable uncertainty. Nevertheless, it may be important to consider them since interactions between temperature and daylength may lead to biological conditions which are not currently experienced anywhere.

4.3.2 Host-enemy synchrony

Hance et al. (2006) state that "a key factor determining how climate change may affect the range and abundance of insect populations is the extent to which individual species react independently of the community of which they are a component. Alteration of the synchronisation between host and parasitoids, by divergence of their thermal preferences can disrupt the equilibrium between host and parasitoid." This synchronisation need not be perfect. In a stable biocontrol system, the level of regulation is such that sufficient hosts and natural enemies survive to the next year to allow similar ongoing regulation in the next. In populations where host and natural enemy have multiple discrete generations a year, imperfect phenological synchronisation allowing some hosts to escape can stablise an otherwise unstable interaction (Godfray et al. 1994).

Climate change can disrupt this stability in several ways.

- Increased temperature may cause one species to come out of diapause earlier than another. The initiation, maintenance and termination of diapause in insects is typically an interaction between daylength and temperature, or daylength alone. A species that has diapause termination regulated solely by photoperiod will have less variation under climate change than one where maintenance and termination is regulated by temperature. Should the species in a biocontrol system have contrasting factors regulating diapause, then it is possible for a large mismatch, control failure and local extinction.
- Increased variability between years. Modelling of a simple host: parasitoid system showed that an abnormally warm spring once in 25 years did not affect the long term stability, but the system failed when if it occurred more frequently than one in 20 years (Godfray et al. 1994).
- Increased generations per year. If either the host of the natural enemy has an additional generation in a season that is not similarly reflected by the other, then stability of the biocontrol system may be at risk
- Loss of synchrony between plant and natural enemy
  - Many weed biocontrol agents in New Zealand are seed feeders and if adult activity is not synchronised with flowering and seed formation, biocontrol will fail. This could happen if the switch from vegetative to reproductive growth is determined by changes in soil moisture and temperature while the weed biocontrol has photoperiod cues. The timing of flowering has been implicated as a factor affecting biocontrol agent performance with flower/seed galling agents (*Urophora solstitialis* and *Rhinocyllus conicus*) on nodding thistle, *Carduus nutans* (Groenteman et al 2008) and with pod/seed attacking insects (*Exapion ulicis* and *Cydia succedana*) on gorse, *Ulex europaeus.* A key factor in achieving widespread establishment of broom seed beetle, *Bruchidius villosus*

- An increased occurrence of warm periods in winter/spring (e.g. more westerly winds predicted) may cause premature emergence of overwintering insects from diapause. This is thought to be responsible for the loss of the first heather beetle *Lochmaea suturalis* 'outbreak' at Tongariro National Park.
- Floral or pollen resources may not be present at the right time.
  - The suppression exerted by *Microctonus hyperodae* on Argentine stem weevil is increased when nectar sources are present in early summer that assist parasitoid adults to survive until host emergence (Phillips et al. 1998, Vattala 2005).
  - Most Diptera natural enemies require pollen in order to produce eggs.
- In a host:parasitoid system the mechanisms controlling development and appearance of life stages can differ between species, giving rise to the possibility of asynchrony which can aid or hinder control.
  - Biocontrol of the lucerne weevil *Sitona discoideus* is successful in New Zealand but not Australia. A small percentage of the parasitised weevil population in New Zealand does not aestivate allowing parasitoid multiplication over summer (see case study).

Passionvine hopper / *Centrodora scolypopae* asynchrony

Both the eggs of the passionvine hopper *Scolypopa australis* and the final instar larvae of its egg parasitoid *Centrodora scolypopae* diapause during winter. The initiation of parasitoid diapause is determined by photoperiod alone. It has been shown that in a current abnormally hot late summer/early autumn, development is too advanced for diapause and the parasitoid larvae pupate, resulting in an unsuccessful partial second generation that is killed by winter temperatures. With low parasitoid numbers in the following year, egg survival in the next hopper generation is very high. Under climate change scenarios, this could become common through Waikato/Bay of Plenty but in Northland the second parasitoid generation should succeed, improving control.

Figure 4.3: A non-parasitised and three parasitised passionvine hopper eggs (eggs cleared with ethanol).

4.3.3 Non-target effects

While the benefits of biocontrol are well known, it is only in recent decades that the potential for negative effects of biocontrol agents on non-target organism has been considered (Barratt et al. 2010). Climate change has the potential to alter how biocontrol agents interact with other species in their environment apart from their target host. This is most likely to bring about negative impacts when previously isolated species are brought into contact through spatial or temporal shifts. We know from recently studied examples that the potential for 'spillover' damage to non-target plant species can increase in cases where the biocontrol agents are present but the plant parts they normally specialise on are absent.

Examples in New Zealand are:
- Broom seed beetle, *Bruchidius villosus*, attacking tagasaste, *Cytisus proliferus*, seed in early spring before broom pods are available (Sheppard et al. 2006).
- Gorse pod moth, *Cydia succedana*, attacking *Lotus* etc when gorse flowers are unavailable (Paynter et al. 2008).
- If ragwort increases its current altitudinal limit in NZ (increased mean temperature and/or reduction in frosts) then there may be an increase in negative effects on rare native *Senecio* spp through more intense apparent competition operating via the native oligophagous magpie moth, *Nyctemera annulata* (Landcare Research/Lincoln University, unpublished data).
- Host range testing at ambient sub-tropical temperatures in Hawaii indicated that a potential fungal biocontrol agent for banana passionfruit was adequately host specific to be considered for release in NZ. However, further testing at lower temperatures better matched to New Zealand, showed that the host range expanded to include the commercial *Passiflora edulis* and possibly the indigenous *P. tetrandra*.
- As mentioned above, climate change could lead to increased use of lucerne in drought-prone regions. This would increase the abundance of Moroccan *Microctonus aethiopoides* in the environment, a species known to attack a range of native weevils.
- Climate change might increase the opportunity for intensification of native grasslands and introduction of exotic pasture species. This might increase the altitudinal range of *Sitona lepidus* and its parasitoid, the Irish biotype of *M.aethiopoides*, and hence bring the parasitoid into closer contact with native grassland-dwelling weevils.

4.4   Population genetics

4.4.1 Capacity for evolutionary adaptation

Evolution is defined as a change in genotype frequencies in a population. Evolution is adaptive when the change in genotype frequencies is caused by natural selection favouring one genotype over another, rather than when the change arises by chance.

Since species have responded to climatic changes throughout their evolutionary history (Root et al. 2003), they are expected to continue to do so under anthropogenic climate change. However, a primary concern is that a rapid rate of climatic change could exceed rates of adaptation (Root et al. 2003, Richardson and Schoeman, 2004; Hampe and Petit, 2005, cited in Hennessy et al. 2007). If species cannot adapt at the pace of climate change, then major changes in distribution are likely, particularly for species at the edges of suitable habitats (Richardson and Schoeman, 2004; Hampe and Petit, 2005, cited in (Hennessy et al. 2007). Rates of evolutionary change in populations under climate

change will depend on levels of heritable variation, genetic interactions among traits, and population processes (Lynch and Lande, 1993). An important consideration for biological control is that, due to genetic bottlenecks, many introduced populations of natural enemies are likely to possess relatively little genetic variation and could have reduced potential for rapid adaptive evolution compared with more heterogeneous natural populations. Also, parthenogenetic biocontrol agents may be even more constrained.

There is already significant evidence for evolutionary shifts in insects exposed to climate change. Examples include recent work on:

- Variation in the timing of egg hatch in winter moths to counter an increasing mismatch between the herbivore and its host (van Asche et al. 2007).
- Variation in thermal responses of the pest beetle, *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae) (Lyytinen et al., 2008).
- Change in photoperiodic response and voltinism in the fall webworm *Hyphantria cunea* following its invasion into Japan (Gomi 1997; Gomi 2004).
- Shifts in genetic markers and phenotypic traits in widespread *Drosophila* spp. and mosquitoes (Bradshaw and Hozapfel, 2001; Hoffmann and Daborn, 2007).

Although only a few studies have addressed evolutionary shifts in natural enemies (Phillips et al. 2008), adaptive responses can be expected for several traits including thermal responses, timing of reproduction and emergence and other traits. Enemies like egg parasitoids of the genus *Trichogramma* spp. that are mass reared for biocontrol typically exhibit rapid adaptation to artificial rearing conditions (Kolliker- Ott et al. 2003) highlighting the potential for rapid evolutionary changes. There is evidence for genetic variation in populations of parasitoids to thermal extremes (Shufran et al. 2004) and evidence for rapid shifts in host adaptation when parasitoids are confined to new hosts (Rolff and Kraaijeveld, 2001; Pannebakker et al. 2008). Predatory mites can be selected for different diapause characteristics that influence their phenology with respect to prey (van Houten et al. 1995). In New Zealand, ragwort flea beetles, *Longitarsus jacobaeae*, introduced from Italy have a summer aestivation that aids survival in summer while other ecotypes used elsewhere in the world do not.

Many parasitoids are univoltine, with generation time synchronized to the number of generations of the host through temperature responses. If herbivores alter voltinism under climate change, parasitoids or predators will need to evolve or respond by plastic changes to synchronize their development with their host (Thomson et al. 2010). There are only a few evolutionary studies in natural enemies that consider synchronization (Phillips et al. 2008), although there is also evidence of genetic variation in generation time in parasitoids (Samara et al. 2008). There is also potential for natural enemies to respond to the altered timing of prey availability through plastic changes, as has been seen in vertebrates such as birds (Seavy et al. 2008), though there are currently no publications to support this.

Whether specialist parasitoids, predators and herbivores, including introduced biological control agents, show much evolutionary potential remains to be seen (Thomson et al. 2010). In New Zealand, the presence of two genotypes of the Argentine stem weevil parasitoid, *Microctonus hyperodae* Loan (Hymenoptera: Braconidae), which exhibit variation in phenology and host synchrony (Phillips et al. 2008) suggests this biological control agent has relatively high potential to adapt to future climatic changes. In contrast, New Zealand populations of some other introduced biological control agents exhibit very little genetic variation and have less potential to rapidly adapt to changing conditions. For example, the Irish strain of *Microctonus aethiopoides* Loan (Hymenoptera: Braconidae) introduced for clover root weevil biocontrol is genetically homogeneous and there is no known phenotypic variation between the two very closely related genotypes introduced to New Zealand (Phillips et al. 2008b). Its adaptive potential could be further restricted by its asexual reproduction (Phillips et al. 2008). The Moroccan *M. aethiopoides* strain introduced for lucerne weevil biocontrol is only marginally more genetically hereogeneous

(Phillips et al. 2008b), though it reproduces sexually and so may have greater potential to adapt to climate change. The herbivorous beetle, *Lochmaea suturalis*, introduced to New Zealand for biological control of heather, *Calluna vulgaris*, are descended from only two female beetles collected from a site in northern England, and genetic studies comparing New Zealand and UK heather beetle populations are consistent with severe bottlenecking of the New Zealand material (Landcare Research unpublished data).

Future studies should consider levels of genetic variation in natural enemies and their hosts, and assess the ability of enemies to track hosts through evolutionary changes, focusing on cases where herbivore pests are already altering their distribution and phenology in response to climate change (Thomson et al. 2010). It may be possible to reduce impacts of climate change on the efficacy of New Zealand biological control agents by increasing their genetic variability and potential for adaptation through introduction of additional genetic stock. However, the host specificity of biological control agents can vary across their native range (Paynter et al 2008, Phillips et al. 2008b, Gerard et al. 2006), so due consideration would need to be given to potential non-target impacts of such introductions.

5. Case studies

This section outlines five representative case studies that demonstrate potential responses of New Zealand biocontrol systems to climate change across the range of scales discussed in the previous section.

- The ragwort biocontrol system shows how the geographic distribution of biocontrol agents may shift in response to climate change, with resulting changes in local pest suppression.
- The tomato fruitworm biocontrol system suggests how climate change may impact local pest population dynamics, potentially exacerbating pest threats beyond the ability of current biocontrols to maintain effective suppression.
- The woolly apple aphid system demonstrates how the generation times of biocontrol agents and their hosts may respond differently to climate change, impacting on the level of pest suppression.
- The lucerne weevil biocontrol system shows how a small difference in parasitoid biology can interact with climate to have a large impact on pest suppression.
- The Argentine stem weevil biocontrol system suggests how genetic variation may influence the ability of biocontrol agents to respond to climate change and maintain effective pest suppression.

5.1   Ragwort biocontrol

The substantial control by ragwort flea beetle, *Longitarsus jacobaeae* (Coleoptera; Chrysomelidae) on its target weed ragwort, *Jacobaea vulgaris* (Asteraceae), is a case study of the potential direct effects of climate change on a weed biocontrol system.

5.1.1 Background

The ragwort flea beetle was first released in New Zealand in 1983 (Syrett 1989). A range of studies document the effect this agent has had on ragwort (Gourlay et al. 2008; Syrett 1989), and the programme has been considered a substantial success (Fowler et al. 2000). However, it is clear that ragwort suppression has not occurred in some parts of the country, notably the West Coast of South Island and some higher altitude and/or westerly regions of North Island (Gourlay et al. 2008).

Ragwort flea beetle has egg, larval and pupal stages on or around the roots of ragwort plants, and a study of the very similar species, *L. flavicornis* in Tasmania has implicated water-logging as a major cause of larval mortality (Potter et al. 2007). Data from three surveys (Gourlay et al. 2005; McGregor 2001; Smith 2003) in New Zealand have been combined in this analysis to produce a relationship of ragwort flea beetle numbers and mean annual rainfall (Figure 5.1.1). Where beetles were sampled across time we used only the highest count on a given date because numbers fluctuated greatly: the maximum recorded numbers were taken as a good indication of whether beetles had *ever* reached high enough levels to lead to weed suppression. Annual mean rainfall was taken from data supplied by NIWA (mean 1971-2000) on a 500m resolution across New Zealand. Points above the dashed line were all those where trends in ragwort density were consistent with successful biocontrol. Where maximum mean beetles numbers per rosette were always <3.5 there was never any indication that beetles were causing any reduction in ragwort densities (Landcare Research unpublished data). For modelling purposes, the threshold for rainfall causing failure of flea beetle suppression of ragwort is 1670mm/year.
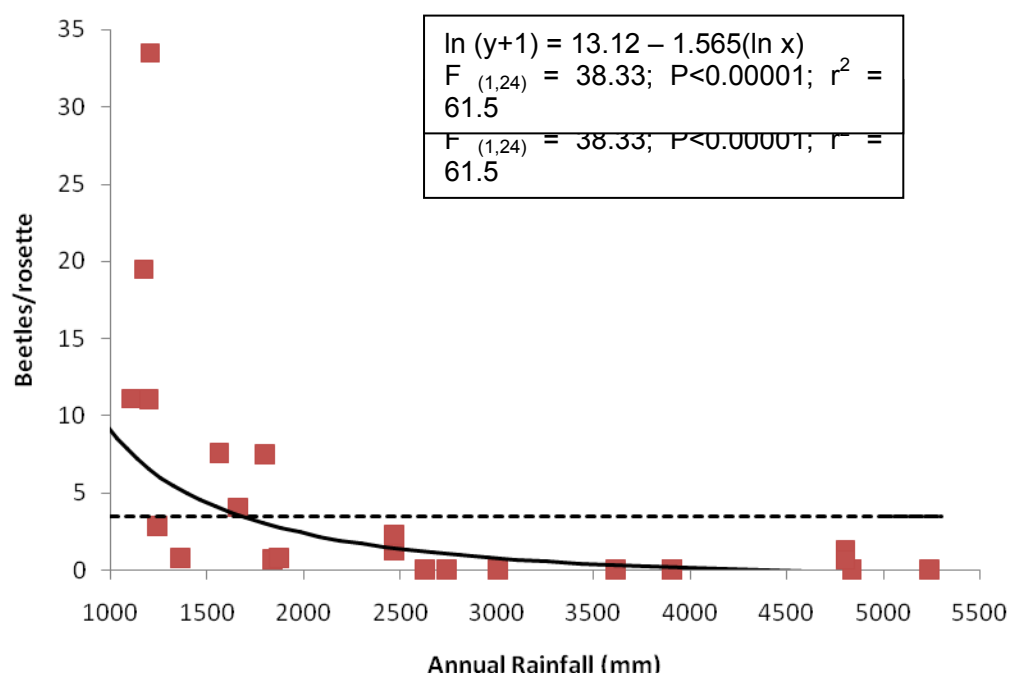
$$\ln (y+1) = 13.12 - 1.565(\ln x)$$
$$F_{(1,24)} = 38.33; \quad P<0.00001; \quad r^2 = 61.5$$

Figure 5.1.1: Mean beetle numbers per rosette per site decline with increasing mean annual rainfall.

5.1.2 Impacts of climate change

A preliminary GIS analysis was carried out to assess the areas above and below the 1670mm/year threshold to predict areas where control is currently likely to be effective or ineffective using the interpolated mean annual rainfall surface 1971-2000 provided by NIWA (Fig. 5.1.2; Table 5.1.1). A threshold of 870mm mean annual rainfall, above which ragwort can grow well in New Zealand (Wardle 1987), was used to estimate how predicted changes in rainfall pattern might affect effectiveness of ragwort biological control "recent", "present" and predicted rainfall regimes.

Table 5.1.1. Total New Zealand land areas in the three mean annual rainfall classes: <870mm/yr – too dry for ragwort; 870-1670mm/yr – ragwort usually suppressed by ragwort flea beetle; >1670mm/yr – conditions usually too wet for ragwort flea beetle).

Annual rainfall range (mm)	1971-2000	Predicted 2040	Predicted 2090
<870mm	4460662 ha	4323225 ha	4196769 ha
870-1670mm	13076409 ha	12961324 ha	13004915 ha
>1670mm	9213157 ha	9382838 ha	9485884 ha

Legend

Mean Annual Rainfall 1971-2000 mm

☐ < 870 (too dry for ragwort)

▨ 870 - 1,670 (effective ragwort control)

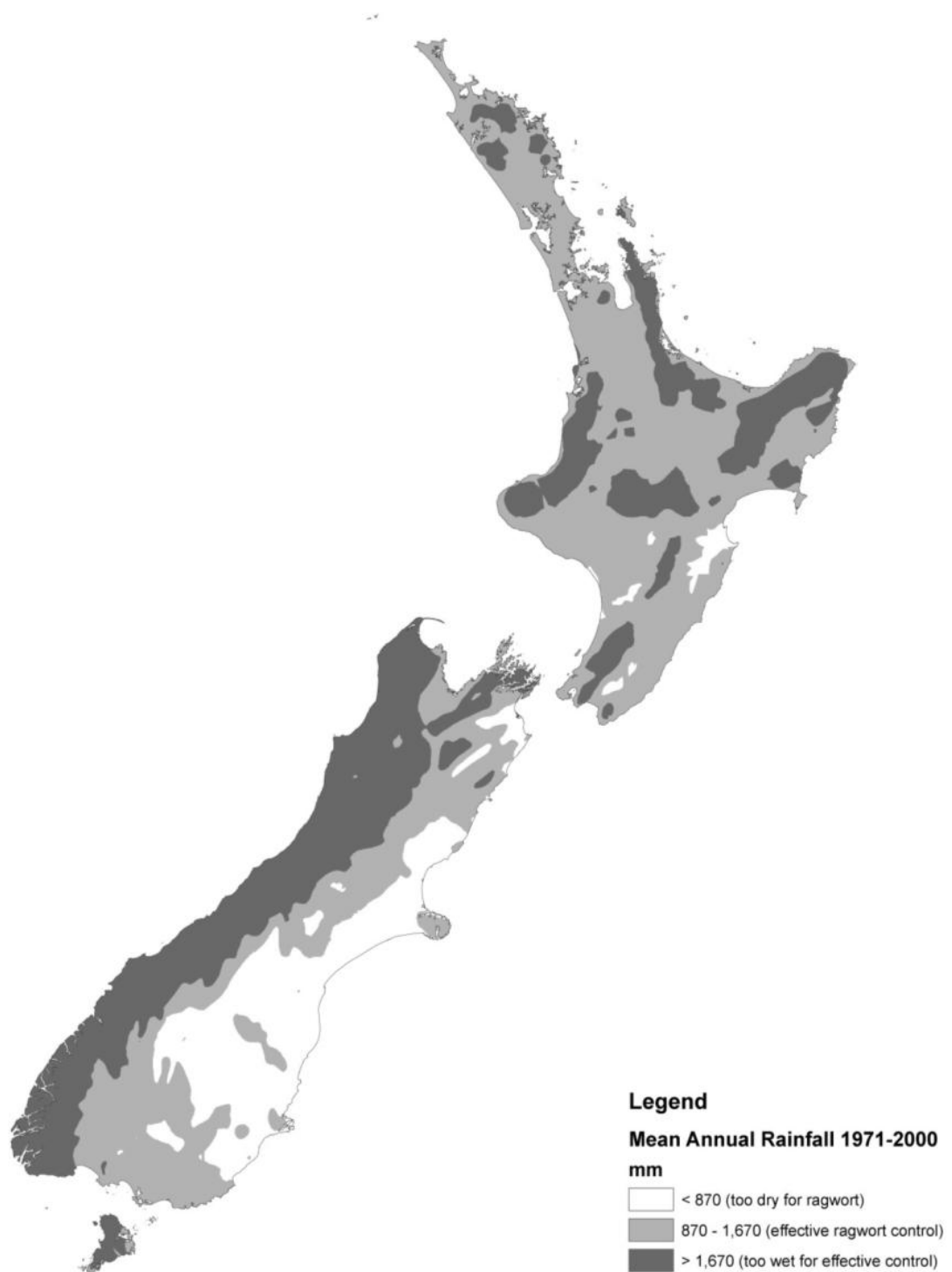■ > 1,670 (too wet for effective control)

Figure 5.1.2. Mean annual rainfall 1971-2000 showing areas with rainfall below 870 mm, 870-1670 mm and above 1670 mm.

The map in Figure 5.1.2 broadly concurs with reports of ragwort flea beetle being ineffective on the West Coast (Gourlay et al. 2008) and in wetter areas of Northland, Taranaki, and Bay of Plenty, but doesn't adequately explain poor performance in Southland (Landcare Research unpublished data). It is possible that temperature is a more important factor than rainfall for ragwort flea beetle performance in the extreme south of New Zealand as low temperatures reportedly limit the same "Italian strain" of the beetle in the USA (Puliafico et al. 2008).

As expected, the climate change scenario predicts an increase in the area where suppression of ragwort by ragwort flea beetle is likely to fail because mean annual rainfall exceeds the model threshold of 1670mm (Table 5.1.1). However, the summed data for New Zealand in Table 5.1.1 obscures the differing trends of predicted biocontrol suppression in the northern part of North Island, where lower annual rainfall under climate change scenarios is likely to increase the land area over which ragwort suppression occurs ("too wet to good control": Table 5.1.2, Figs 5.1.3 and 5.1.4).

There are also areas, particularly in South Island, where ragwort might be expected to extend its current range (as rainfall increases above the 870 mm/yr threshold) but where the ragwort flea beetle should follow the range expansion of the plant and usually give adequate suppression ("too dry to good control": Table 5.1.2, Figs 5.1.3 and 5.1.4).

In the east of New Zealand there are also areas that are predicted to drop below a mean annual rainfall of 870 mm, thus in theory becoming too dry to sustain ragwort ("good control to too dry": Table 5.1.2, Figs 5.1.3 and 5.1.4). However the plant is likely to be already under good control by ragwort flea beetle in these areas, so no significant benefit to farmers would accrue.

The land areas shown in Tables 5.1.1 and 5.1.2 and illustrated in Figures 5.1.2 to 5.1.4 need to be viewed with caution (e.g. the 600409 ha of land where ragwort flea beetle suppression might fail: "good control to too wet" 2090 scenario in Table 5.1.2) as this preliminary analysis does not take into account critical factors such as land use. As a result, the real figure of pasture at potential risk from new ragwort invasion, or conversely where the weed is likely to come under good biocontrol suppression, cannot be ascertained. Ragwort is mainly an issue for cattle and dairy herds (Syrett 1989 and references therein), so a more refined analysis could use data such as Agribase which provides information on farm type, to isolate those parts of the country where ragwort infestation might be a significant threat. Clearly, any further economic analysis was not appropriate without a much more detailed set of predictions incorporating land use.

Finally, a further analysis could incorporate predictions of the impact of another recently released biological control agent for ragwort, the plume moth, *Platyptilia isodactylus*. This agent was released especially to target ragwort infestations in wetter regions of New Zealand, and has already established well in some sites on the West Coast of South Island (Landcare Research unpublished data).

Table 5.1.2. Changes predicted to occur in the New Zealand land areas in the three mean annual rainfall classes: <870mm/yr – too dry for ragwort; 870-1670mm/yr – ragwort usually suppressed by ragwort flea beetle; >1670mm/yr – conditions usually too wet for ragwort flea beetle). These changes are illustrated in Figures 5.1.3 and 5.1.4.

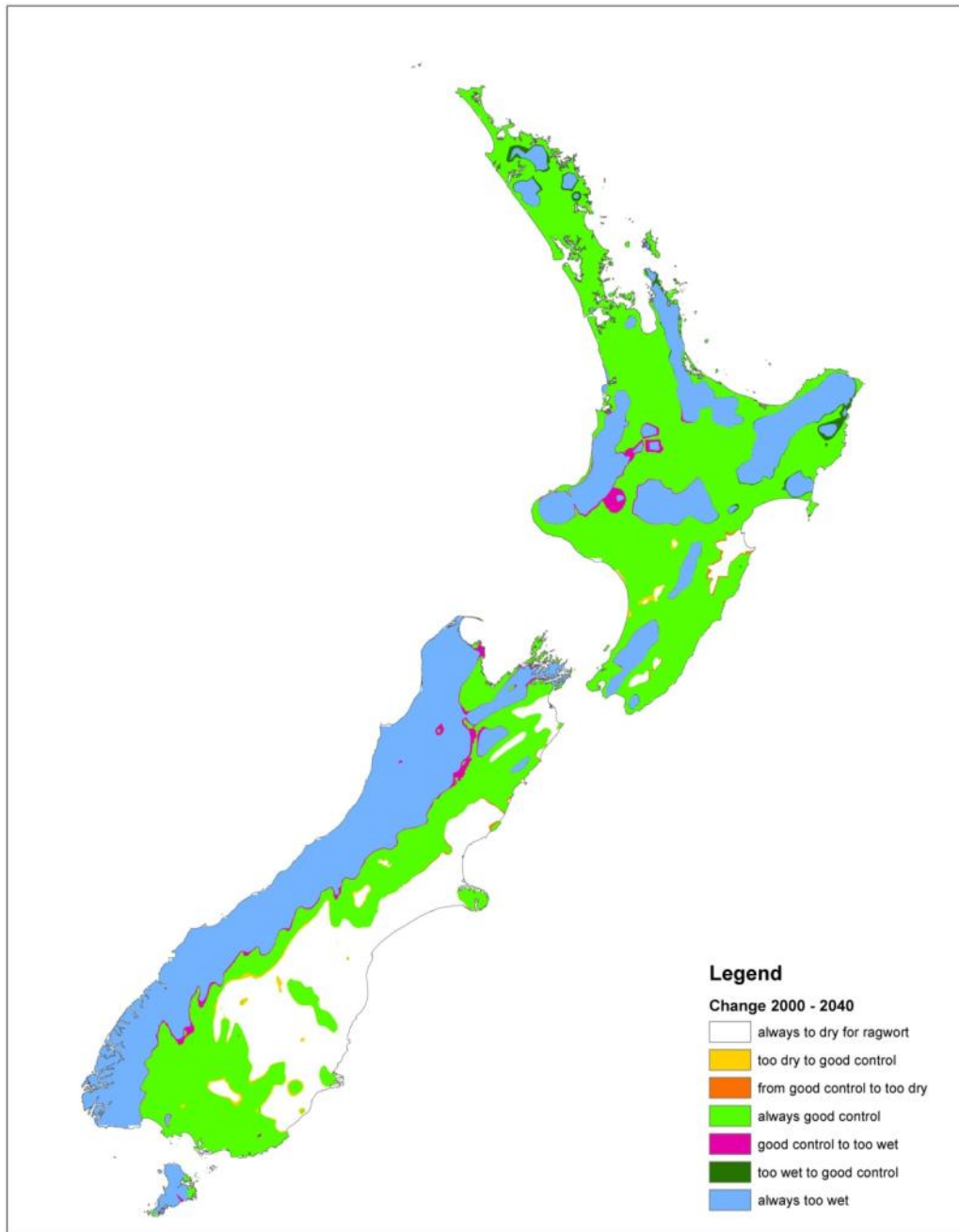| Rainfall change category	Text explanation (used on Figures 3 & 4)	Predicted area in 2040	Predicted area in 2090
Always < 870 mm	Always too dry for ragwort	4260711 ha	4107848 ha
< 870 to > 870	Too dry → good control	194295 ha	352290 ha
> 870 to < 870	From good control → too dry	62514 ha	88912 ha
Always 870 – 1670	Always good control	12564702 ha	123267687 ha
< 1670 to > 1670	Good control → too wet	408140 ha	600409 ha
> 1670 to < 1670	Too wet → good control	202327 ha	284938 ha
Always > 1670	Always too wet for control	8974698 ha	8885475 ha

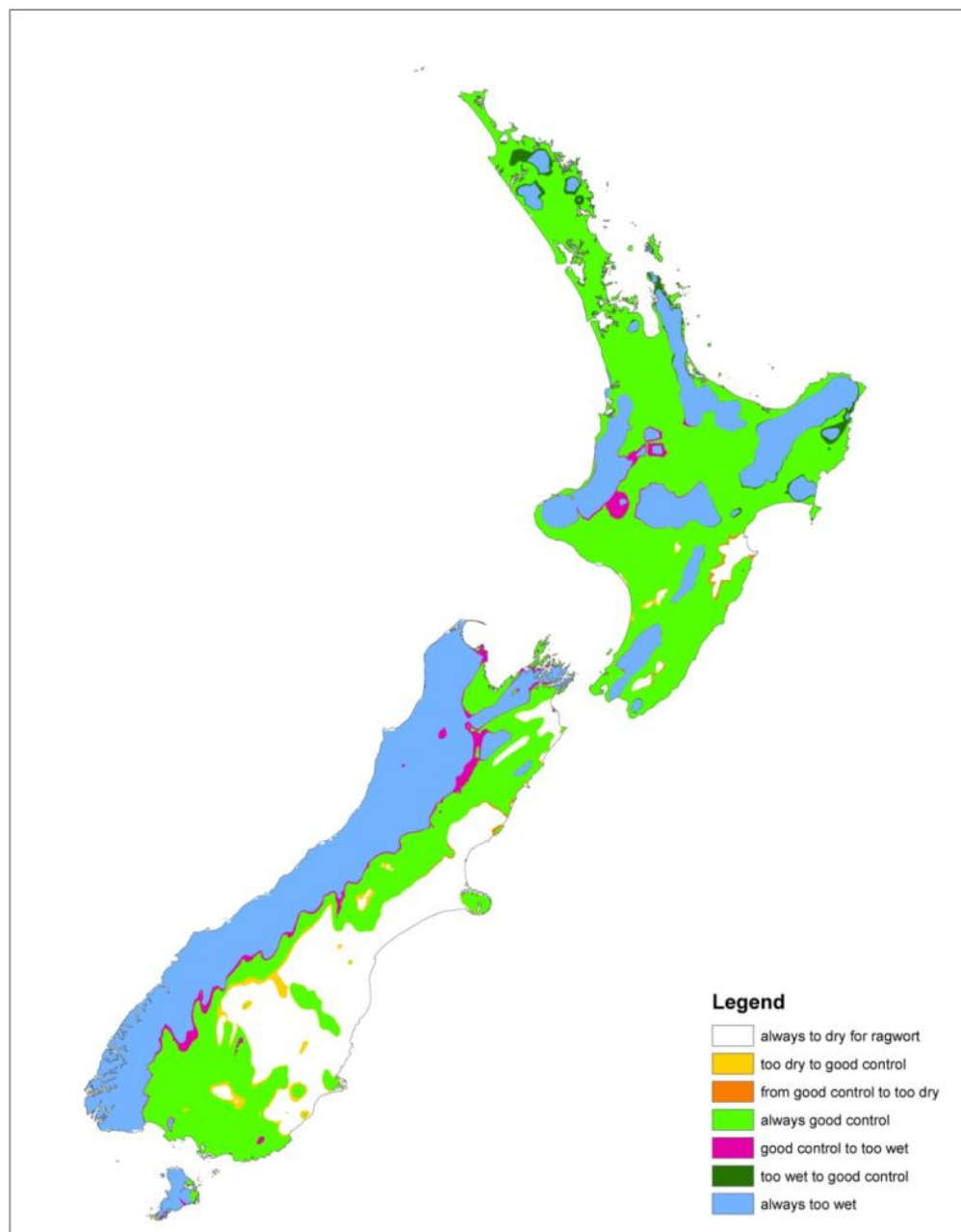**Figure 5.1.3: Predicted land areas for mid-range emission scenario A1B for 2040.**

Figure 5.1.4: Predicted land areas for mid-range emission scenario A1B for 2090.

5.2 Tomato fruitworm biocontrol

This case study suggests how climate change may allow more pest generations to develop each season, potentially exacerbating pest threats beyond the ability of current biocontrols to maintain effective suppression.

5.2.1 Background

Helicoverpa armigera (Hübner) (Lepidoptera: Noctuidae), commonly known as tomato fruitworm, corn earworm or heliothis in New Zealand, has a very wide host range. Larvae feed mainly on flower buds, flowers, developing seeds and fruits, and sometimes foliage. They are a major pest on maize/sweet corn, tomato, cabbage, lettuce, lucerne, lupins and conifer seedlings. They also attack peas, beans, pumpkins and marrows, tobacco, clover and linen flax and a great number of ornamental herbaceous plants and shrubs (Valentine, 1984). *H. armigera* is the key insect pest of processing tomatoes in the main growing region of Hawke's Bay, where it damages up to 30% of fruit in unsprayed late season crops (Walker and Cameron, 1990). To counter this, two larval parasitoids were successfully introduced into New Zealand: *Cotesia kazak* (Telenga) (Hymenoptera: Braconidae) in 1977, and *Microplitis croceipes* (Cresson) (Hymenoptera: Braconidae) in 1986 (Walker and Cameron, 1989). These now cause 60 to 80% parasitism of *H. armigera* (Cameron et al. 2006). *C. kazak* is the dominant parasitoid, reared from about 90% of parasitized larvae, and it usually kills before the larvae are able to locate and damage tomato fruit (Cameron et al. 2001). The parasitoids now form the basis of an integrated pest management (IPM) programme to control *H. armigera* on outdoor tomato crops (Cameron et al. 2001; Walker et al. 2010).

H. armigera normally has three generations a year in the north, but in cooler summers and in cooler regions there are often only two generations a year (Walker & Cameron 1990). Despite the action of the parasitoids, the third generation, when present, can lead to severe crop losses in sweet corn, tomatoes and leafy vegetable crops such as cabbage and lettuce. In areas where it common, the damage caused by this third generation currently prevents the processing industry from planting late crops of sweet corn and processing tomatoes.

Figure 5.2.1: *Helicoverpa armigera* **larva on tomato.**

5.2.2 Impacts of climate change

The expected climate warming may allow a third generation of *H. armigera* to occur in cooler seasons and in cooler regions. This would have a major impact on the pest status of *H. armigera* in these areas, particularly in the South Island where the key parasitoid, *C. kazak* is not currently present. The timing of *H. armigera* flights in New Zealand is

successfully predicted from a generational day degree requirement of 475 °d above a threshold temperature of 11 °C (G. Walker, pers. comm.). These parameters suggest more rapid development in NZ populations than in Australian (Allsopp et al. 1991), Japanese (Jallow & Matsumura 2001), and North American (Younis & Ottea 1993) populations, but slower than those in Greece (Mironidis & Savopoulou-Soultani 2009). Since the threshold temperature for development of the parasitoids is similar to that for the pest (calculated from data presented by Tillman & Powell 1991 and Tillman et al. 1993), the GTRs are constant with temperature. The GTR for *C. kazak* (GTR = 0.39) is lower than that of *M. croceipes* (GTR = 0.52), which matches the observation that *C. kazak* is the more effective biocontrol agent.

These development parameters were used to calculate the expected number of *H. armigera* generations per year across New Zealand, assuming a biologically active season from 1 September to 1 May (Dillon 1998). The results are shown in Figure 5.2.1, where the presence of problematic third and fourth generations are indicated by yellow and red colours, respectively. The results suggest that even under a moderate emissions scenario *H. armigera* is expected to become increasingly problematic, and by 2090 may be affecting late season crops of tomato and corn as far south as Canterbury. However, it is not yet known how the parasitoid complex may react under conditions sufficient for four host generations per season. Given that *C. kazak* has not been effective at controlling *M. armigera* in warmer areas overseas, the future viability of the current IPM systems may be compromised.
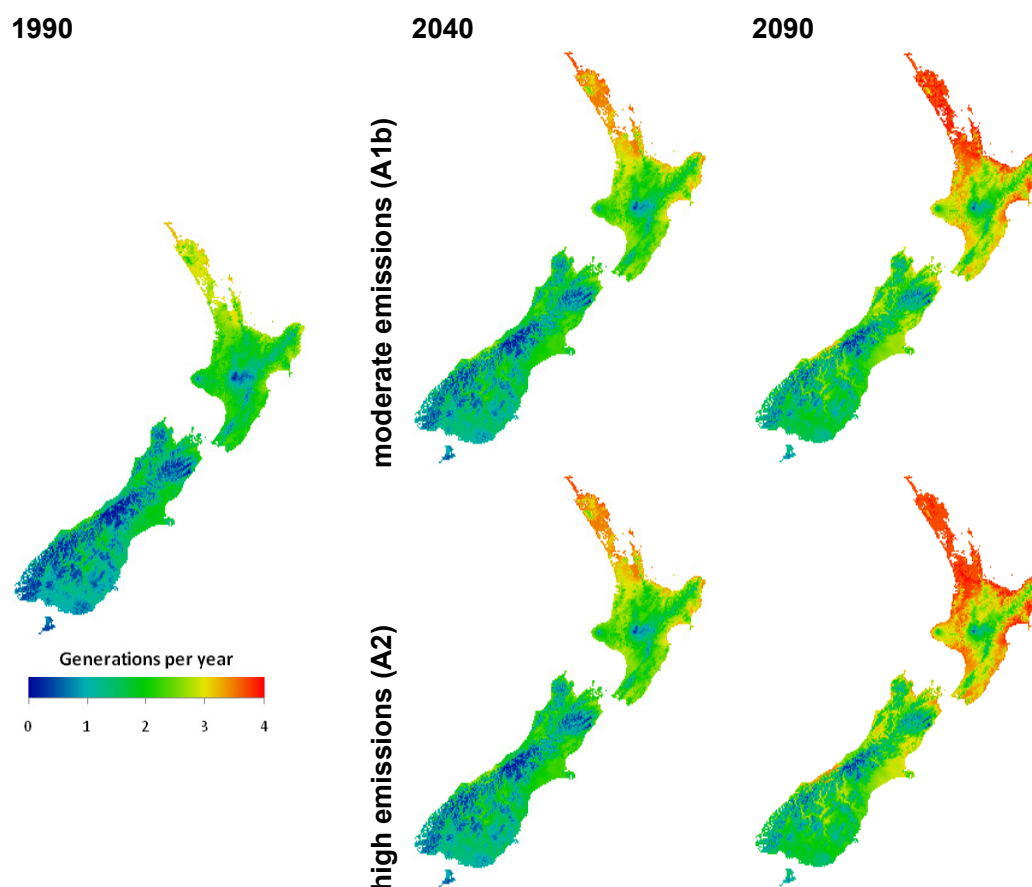

Figure 5.2.1. **The number of annual generations of *Helicoverpa armigera* expected in New Zealand under current and future climates.**

5.3 Woolly apple aphid biocontrol

This example shows how differences in the developmental temperature thresholds and diapause behaviours of pest and biocontrol agent can interact in different ways, making it difficult to predict the outcomes from climate change.

5.3.1 Background

The woolly apple aphid, *Eriosoma lanigerum* (Hausemann) (Hemiptera: Pemphigidae), is a serious pest of apples throughout the world. It has a short development time, with many overlapping generations per year. In New Zealand, populations persist year round on the shoots and exposed roots of apple trees, and reproduction is almost exclusively asexual.

Management of *E. lanigerum* in New Zealand orchards relies on the parasitoid, *Aphelinus mali* (Hald.) (Hymenoptera: Aphelinidae) as part of an integrated fruit production system (Shaw & Walker 1996). Like its host, *A. mali* has multiple overlapping generations, with 5 to 15 per year having been reported internationally (Hagen & van den Bosch 1968). Unlike its host, however, *A. mali* enters a diapause in autumn, which is terminated in mid-winter. The early spring period is critical for the population dynamics of this biocontrol system, since bud burst creates optimal conditions for reproduction of the host while post-diapause parasitoids may not yet have matured. The IPM system in New Zealand may require insecticide application in October to temporarily suppress *E. lanigerum* until *A. mali* becomes active (Shaw & Walker 1996, Shaw & Wallis 2009).

5.3.2 Impacts of climate change

This biocontrol system contains several factors that suggest that climate change could influence biocontrol success. First, the host and parasitoid differ in their thermal development thresholds: aphid = 5.2 °C (Asante et al. 1991); parasitoid = 8.3 °C (Asante & Danthanarayana 1992). Since the aphid's threshold temperature is lower than that of the parasitoid, the GTR is high at low temperatures (Fig. 5.3.1), and biocontrol is expected to be least successful in cool areas. This is indeed the case, with biocontrol being ineffective in countries with cool, cloudy summers (DeBach & Rosen 1991). Under predicted future warming, then, biocontrol might be expected to be more successful overall.
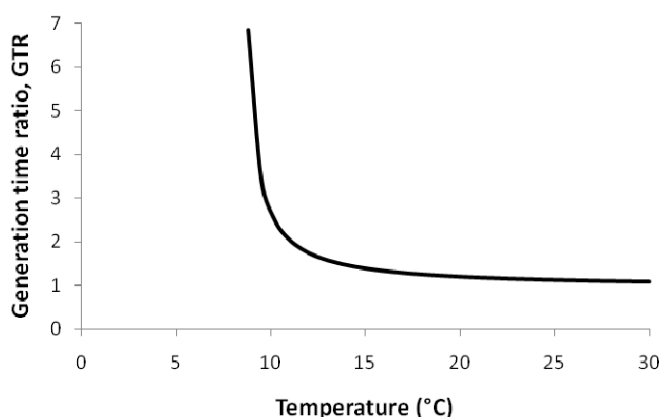

Figure 5.3.1. Generation time ratio GTR for the parasitoid *Aphelinus mali* attacking the woolly apple aphid *Eriosoma lanigerum* at constant temperatures.

However, *A. mali* has a winter diapause, from mid September (Hagen & van den Bosch 1968) to the end of January (Trimble et al. 1990) in the Northern Hemisphere, whereas

the aphid continues to develop year-round. Assuming that the diapause period remains unchanged under future climates, warmer winters may allow greater aphid population increase during parasitoid diapause and greater damage to orchards in spring. This runs counter to the previous argument which was based on threshold temperatures alone.

Figure 5.3.2 shows the predicted GTR for for *E. lanigerum* and *A. mali* in New Zealand under current and future climates, taking both factors into account. The development period for the parasitoid was limited as August to mid-March (offset by 6 months from the Northern Hemisphere active period) whereas the aphid was assumed to develop all year, providing that daily temperatures are sufficient. This analysis suggests that climate change effects on this biocontrol system are likely to be minor, with perhaps slightly better suppression overall, especially in the North Island. However, the results suggest that *E. lanigerum* might complete up to one additional generation during the winter, so that pest densities might be slightly greater in early spring. Therefore, a targeted aphicide spray in early spring is likely to remain an important part of the integrated fruit production systems for New Zealand apples (Shaw & Wallis 2009).
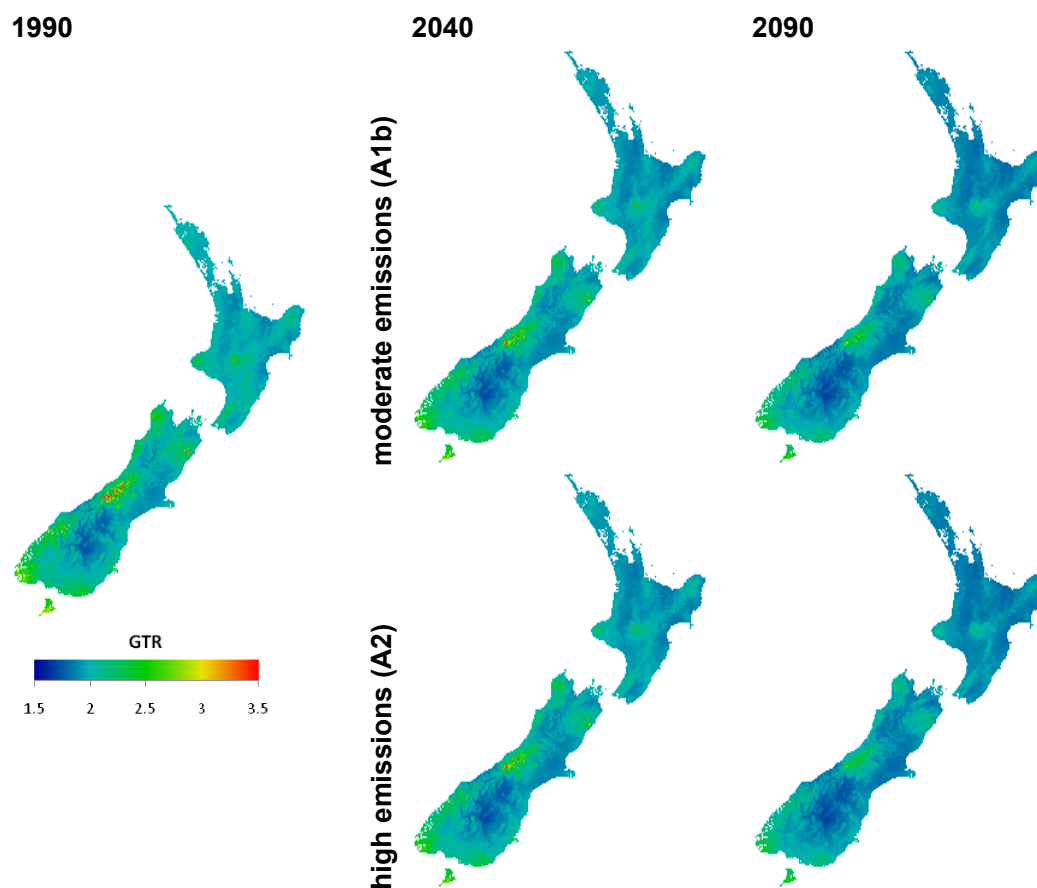

Figure 5.3.2. The influence of future climates on generation time ratio GTR for *E. lanigerum* and *A. mali* in New Zealand.

5.4   Lucerne weevil biocontrol

This case study exemplifies: (i) how the performance of biological control agents can be critically dependent on subtleties of their interactions with host populations; (ii) how a subtle but critically important population interaction seems to have arisen from a peculiarity of New Zealand's climate; and (iii) how this could be impacted by climate change.

5.4.1 Background

Lucerne weevil, *Sitona discoideus* Gyllenhal (Coleoptera: Curculionidae), is a Mediterranean species that was discovered in 1975 to have been accidentally introduced to New Zealand (Esson 1975). It became a severe pest of lucerne and a comprehensive, long term, population dynamics study ensued as a basis for pest management (Goldson et al. 1988). In 1982, the parasitic wasp *Microctonus aethiopoides* Loan (Hymenoptera: Braconidae) was introduced for biological control of *S. discoideus* (Goldson et al. 1990; Barlow & Goldson 1993; Kean & Barlow 2000).The lifecycle of *M. aethiopoides* is as follows: the adult parasitoid lays an egg in an adult weevil, whereupon a solitary larva develops within the live host. The mature larva then emerges to pupate, while the host dies due to the parasitism. One *M. aethiopoides* female can lay an egg in each of up to about 100 weevils (Phillips & Baird 2001).

In New Zealand, as in Australia (Cullen & Hopkins 1982) and southern Europe (Aeschlimann & Vitou 1988), *S. discoideus* has one generation per year. The weevil over-summers as a pre-reproductive adult in a sheltered place away from lucerne, presumably as an adaptation to surviving hot, dry conditions (termed 'aestivation'). It returns to the lucerne in autumn and commences reproduction which continues until spring. The *M. aethiopoides* larva generally only develops when its host is reproductive. The parasitoid over-summers as a non-developing larva in an aestivating *S. discoideus* and then resumes its development once its host has returned to the lucerne. Under these conditions, *M. aethiopoides* has two generations for every host generation (GTR = 0.5). This occurs in its natural range in Europe, and in Australia where, with a GTR of c. 0.5, *M. aethiopoides* is not a particularly effective biocontrol agent (Hopkins 1989). However, in New Zealand and unlike anywhere else, c. 3% of *S. discoideus* still support parasitoid development throughout summer even though they remain non-reproductive. These weevils, which stay in the lucerne, support an additional four parasitoid generations. This unusual population interaction reduces the GTR to less than 0.2, and is thought to be critical to the very effective control of *S. discoideus* exerted by *M. aethiopoides* in New Zealand (Goldson et al. 1990; Barlow & Goldson 1993; Kean & Barlow 2000).

The basis for this uniquely New Zealand population interaction is unknown, but could be due either to genetic variation in *M. aethiopoides* and/ or *S. discoideus*, or to a seasonal effect that enables parasitoid larvae to develop in newly eclosed weevils and disrupt the sympathetic aestivation of both species (Goldson et al. 1990). Genetic explanations seem unlikely because there is only minor genetic variation between New Zealand and Australian populations of *M. aethiopoides* (Phillips et al. 2008b) and *S. discoideus* (Vink & Phillips 2007). Also, in New Zealand, selection would strongly favour non-aestivating genetic variants of *M. aethiopoides*, and strongly disadvantage non-aestivating variants of *S. discoideus*. However, the proportion of *M. aethiopoides* and *S. discoideus* exhibiting the atypical behaviour consistently remained around 3% (Goldson et al. 1990; Barlow & Goldson 1993) which does not suggest strong selection. The most likely reason for the atypical behaviour therefore appears to be seasonal differences in climate (perhaps interacting with daylength) between New Zealand and other regions such as Australia and Mediterranean Europe.

5.4.2 Impacts of climate change

Lucerne is expected to become an increasingly important fodder crop in eastern parts of New Zealand as they become generally drier (Fig. 2.2). However, as New Zealand's climate becomes more like those of Australia and Mediterranean Europe, there is a risk that the atypical interaction between *M. aethiopoides* and *S. discoideus* may cease and biological control become less effective (Goldson 2006).

Examination of mean monthly temperatures suggests that areas of New Zealand where the biocontrol is currently successful may become increasingly similar to Australian areas where biocontrol is ineffective (Fig. 5.4.1). The same result arises from the use of CLIMEX's "match climates" function (Fig. 5.4.2). If the success of *M. aethiopoides* at controlling *S. discoideus* in New Zealand is related to climate, then it is possible that this currently successful biocontrol will become ineffective under future climates. Until the mechanistic trigger for atypical parasitoid development in New Zealand is known, it will not be possible to assess how likely the break-down of biocontrol success is. In the meantime, lucerne growers should be alert for weevil outbreaks that may signal that the biological controls are becoming ineffective.

Figure 5.4.1: **Comparison of mean daily maximum (solid lines) and minimum (dashed lines) temperature between four locations in South Australia where *M. aethiopoides* is ineffective against *S. discoideus* (blue lines) and Darfield, New Zealand, where biocontrol is effective (green lines = current climate, red lines = forecast for 2090, scenario A2).**

Figure 5.4.2: **CLIMEX comparison of current (top) and potential future (2090, scenario A2, bottom) climates for central Canterbury against current Australian climates.**

5.5   Argentine stem weevil biocontrol

This case study exemplifies: (i) how within-species genetic variation enables a biological control agent to adapt to annually changing conditions; and (ii) how in this case the adaptive evolution is linked to climate and, therefore, how within-species genetic variation could assist this biological control agent to cope with climate change. The case study then discusses the possibility that some important introduced biological control agents probably possess minimal within-species genetic variation, so have less potential to genetically adapt to climate change.
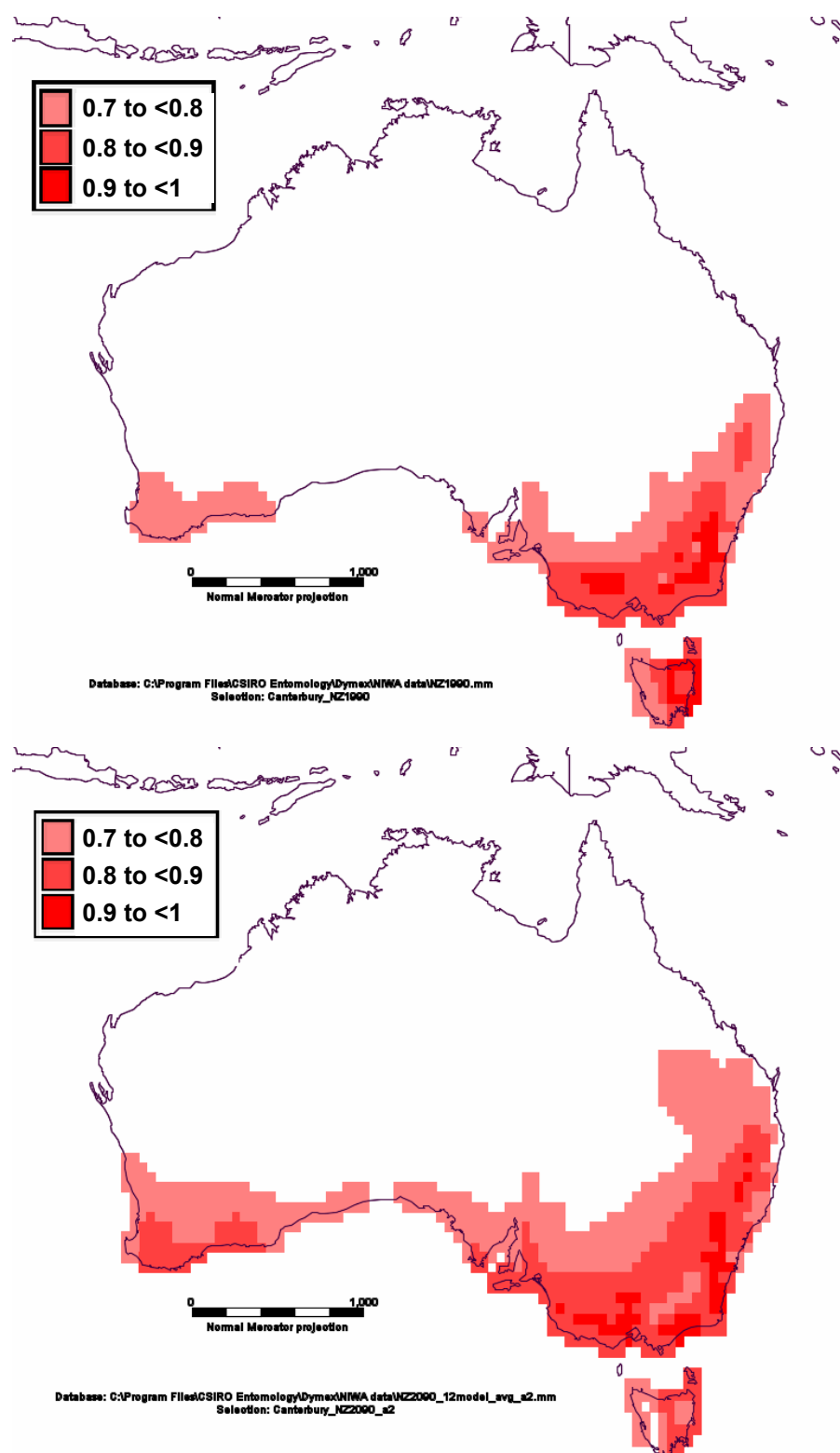
5.5.1 Background

Argentine stem weevil, *Listronotus bonariensis* (Kuschel) (Coleoptera: Curculionidae), was first recorded in New Zealand in 1927 (Marshall 1937) and it now occurs in pasture throughout the country (McNeill et al. 2002), equating to 10 million ha (MAF 1997). New Zealand *L. bonariensis* populations are genetically homogeneous and exhibit less variation than South American populations, possibly due to a bottleneck during colonization (Williams et al. 1994). In 1991, an asexually reproducing South American parasitoid wasp, *Microctonus hyperodae* Loan (Hymenoptera: Braconidae), was introduced for biological control of *L. bonariensis*, its only known host (Loan & Lloyd 1974, McNeill et al. 2002). It lays one egg per adult weevil, the weevil is reproductively sterilised but remains active until the parasitoid larva developing within it emerges to pupate, when the weevil dies (Loan & Lloyd 1974).

Equal numbers of seven "ecotypes" of *M. hyperodae* from different South American sites were released to allow analysis of establishment patterns and the role habitat pre-adaptation (Goldson et al. 1993). There were two main genotypes, one from east of the South American Andes mountains and another from the west (Phillips et al. 2008a). The frequency of each genotype was measured in *M. hyperodae* populations collected from 14 New Zealand sites for 1-10 years following release and, at most sites in most years, selection favoured the eastern genotype (Phillips et al. 2008a). At Lincoln, where annual fluctuations in the frequencies of the two genotypes were studied most intensively and for longest (Phillips et al. 2008a), the fluctuations were correlated with variations in annually accumulated day degrees, with the frequency of the western genotype increasing in warmer seasons (Phillips et al. unpublished). The reasons why selection has favoured the eastern genotype in most years at most New Zealand sites is currently being clarified, but is probably related to observed differences in phenology between the genotypes (discussed below).

Figure 5.5.1 shows the frequency of eastern *M. hyperodae* at Lincoln from 1991 to 2001 (Phillips et al. 2008a). Selection favouring the eastern genotype occurred in 1993 and 1994 (P < 0.01), which were particularly cool years, and selection favouring the western genotype occurred in 1998 (P < 0.01), which was particularly warm (Phillips et al. unpublished). The presence of the two *M. hyperodae* genotypes in New Zealand has enabled the biological control agent to make annual adaptive responses, apparently to seasonal temperature variations; this has enabled a stronger, more stable and more persistent suppressive effect to be exerted on *L. bonariensis* than would have been the case if just one genotype had been present (Phillips et al. 2008a).
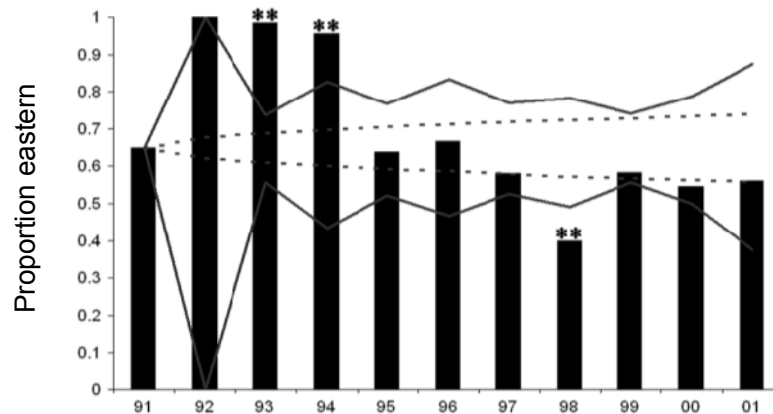
Figure 5.5.1: Frequency of eastern *Microctonus hyperodae* in samples collected at Lincoln, 1991 – 2001. Dashed horizontal lines show expected random variation from genetic drift, and solid horizontal lines show expected variation from genetic drift plus sampling error (Phillips et al. 2008a).

A major difference between the genotypes observed at Lincoln is that adults of the eastern genotype emerge earlier in summer than western adults; they also emerge well before the first summer generation of its adult weevil hosts (Phillips et al. unpublished). This early emergence is initially disadvantageous because few weevil adults are available for parasitism, but it can later become beneficial because it increases the time available for an extra parasitoid generation before autumn. In contrast, the western genotype's later emergence coincides with an abundance of hosts so is initially beneficial, but it also constrains the number of generations possible before autumn. One hypothesis to explain the observed frequencies of the two genotypes (Fig. 5.5.1) is that the eastern one becomes dominant following seasons with cool autumns because their early emergence enabled them to undergo an additional generation compared to their western competitors. However, the western genotype becomes dominant following seasons with relatively warm autumns because it undergoes the same number of generations as its eastern competitor, and it retains the initial advantage of its higher reproductive rate in early summer (Phillips et al. unpublished).

5.5.2 Impacts of climate change

The above hypothesis can be used to forecast the balance between the *M. hyperodae* genotypes under future climates. Table 5.5.1 summarises the probable number of parasitoid generations in cool and warm seasons for each parasitoid genotype. Under current climates the dominant genotype will vary between cool and warm seasons, while medium term (2040) warming will generally favour the western genotype, but strong long-term warming (scenario 2090 A2) will favour the eastern genotype.

Table 5.5.1: Phenological model predictions for the number of annual generations of *Microctonus hyperodae* genotypes from east (E) and west (W) of the Andes under different climate scenarios in New Zealand.

Climate scenario	Cool season (e.g. 1993) Generations (E:W)	Dominant	Warm season (e.g. 1998) Generations (E:W)	Dominant
current	2:1	E	2:2	W
2040 A1B	2:2	W	3:3	W
2090 A1B	2:2	W	3:3	W
2040 A2	2:2	W	3:3	W
2090 A2	3:2	E	4:3	E

These results are preliminary because the models did not consider some important factors such as how climate change could influence the summer emergence date of first generation *L. bonariensis* adults. However, they serve to demonstrate how climate change will inevitably impose new selection pressures on biocontrol agents, and how genetic diversity within biocontrol agents will be important for them to adapt to those new pressures. The introduction of two *M. hyperodae* genotypes to New Zealand has increased the efficacy of the biocontrol programme because one compensates for the other as climatic conditions fluctuate, so together they maintain high rates of parasitism of the pest (Phillips et al. 2008a). If the eastern genotype alone had been introduced, then pest suppression would be lower in warm years, and also under the moderate climate change scenario. However, if only the western genotype had been introduced, then suppression would be less in cool years, and probably also under the extreme climate change scenario. Genetic variation within *M. hyperodae* therefore enhances the current biological control of *L. bonariensis* (Phillips et al. 2008a), and increases the resilience of this biocontrol system to future climatic changes.

There are a few other examples which indicate that genetic variation within biocontrol agents enhances their performance under climatic variation. *Trioxys complanatus* Quilis (Hymenoptera: Aphidiidae) was introduced to California from Iran and Italy during the 1950's as a biological control agent of the spotted alfalfa aphid *Therioaphis trifolii* (Monell) (Homoptera: Aphididae) (Flint, 1980). An investigation of the climatic adaptations of *T. complanatus* collected during the mid 1970's from Iran, Italy and California's central valley found that Italian parasitoids lacked an aestival diapause and suffered very high mortality in temperatures above 26°C. It was reasoned that the Californian and Iranian populations were adapted to hot, dry summers and very cold winters while the Italian population was adapted to a milder coastal climate (Flint, 1980). Observed similarities between the Californian and Iranian populations suggested that, of the original introductions from Italy and Iran in the 1950's, the Iranian-sourced parasitoids were those that had become prevalent in the central valley of California (Flint, 1980). Another example involves a French strain of *Trioxys pallidus* Haliday which parasitises the walnut aphid, *Chromaphis juglandicola* Kaltenbach (Homoptera: Aphidiidae). This parasitoid was introduced into California in 1959 and established in the cooler southern coastal areas of California, but did not establish in the hotter San Joaquin Valley despite repeated introductions (van den Bosch et al. 1979). An Iranian *T. pallidus* strain was introduced in 1968 and rapidly colonised the San Joaquin Valley as well as Oregon and suppressed the walnut aphid (Unruh & Messing 1993).

Unfortunately, the capacity of most introduced biocontrol agents to adapt to climatic changes is probably limited by low levels of genetic variation in their introduced populations. Compared with most other biological control programmes, extraordinary efforts were made to collect *M. hyperodae* genetic variation from throughout southern South America, maintain it during laboratory culturing, then ensure all of it was released

in New Zealand (Goldson et al. 1992, Goldson et al. 1993, McNeill et al. 2002). In contrast, resource limitations and other practical considerations have limited attempts to establish genetically diverse populations of biocontrol agents in New Zealand and elsewhere. For example, another parasitoid, *Microctonus aethiopoides* Loan, was introduced from Morocco to Australia for biological control of lucerne weevil, *Sitona discoideus* Gyllenhal (Coleoptera: Curculionidae) (Aeschlimann, 1995). A subsample of material from New South Wales was then introduced to New Zealand (Stufkens et al. 1987). The outcome of this process of population subsampling has been that, in New Zealand, the lucerne weevil biocontrol agent possesses much less genetic variation compared with overseas populations (Vink et al. 2003, Phillips et al. 2008b). Similarly, the clover root weevil (*Sitona lepidus* Gyllenhal) biocontrol agent, another strain of *M. aethiopiodes*, was introduced to New Zealand from several sites in Northern Ireland (McNeill et al. 2006) and possesses very little genetic variation compared with overseas populations (Phillips et al. 2008b). Another example is the beetle, *Lochmaea suturalis* (Coleoptera: Chrysomelidae), introduced to New Zealand for biological control of heather, *Calluna vulgaris* (Ericales: Ericaceae). The New Zealand population is descended from only two female *L. suturalis* collected from a site in northern England, and genetic studies comparing New Zealand and UK heather beetle populations are consistent with severe bottlenecking of the New Zealand material (Landcare Research unpublished data).

Future studies should consider levels of genetic variation in natural enemies and their hosts, and assess the ability of enemies to track hosts through evolutionary changes, focusing on cases where herbivore pests are already altering their distribution and phenology in response to climate change (Thomson et al. 2010). It may be possible to reduce impacts of climate change on the efficacy of New Zealand biological control agents by increasing their genetic variability and potential for adaptation through introduction of additional genetic stock. However, the host range of biological control agents can vary across their native range, so due consideration would need to be given to potential non-target impacts of such introductions. Indeed, regulators are now quite keen on conditional release of biocontrol agents from a particular locality that matches the material used in host range tests. It will mean that biocontrol programmes will need to address this in containment testing.

6.   Conclusions

The main effect of the climate warming forecast for the next century will be a tendency for species ranges to move south to follow their preferred climate conditions and shifting crop distributions. However, this depends on the dispersal ability of pests and their biocontrol agents. Some species will have little opportunity to move southward, either because of poor dispersal ability or spatially disjunct habitats. This may be particularly true for native species confined to land managed for conservation that cannot necessarily shift as other land uses may. Non-target hosts in particular may be exposed to new, southward or altitudinally shifting pests and generalist natural enemies. A major barrier to the southward movement will be Cook Strait, which presents both a potential opportunity for slowing the spread of pests into the South Island, but also may require biocontrol agents to be actively imported (e.g. *Cotesia kazak*, which is not currently present in the South Island though its host is).

The overall southward trend will be complicated by several factors. First, there is expected to be a change in the frequency of weather patterns resulting in more subtle changes such as the east becoming drier while the west becomes wetter. This will influence the future distributions of some pests and their biocontrol agents (e.g. ragwort biocontrol case study). Related to this, it is expected that the frequency of extreme events (droughts, floods, heavy frosts, high winds) will increase, which may temporarily disrupt some biocontrol systems. In addition, many species respond to factors like daylength that will not change. Pests and their biocontrol agents may respond differently to the north-south influence of temperature, the east-west influence of rainfall, and the unchanging cycle of daylengths, resulting in unique new combinations for which we cannot currently predict the outcome. In these new situations, the success of biocontrol systems may depend on adaptation to local conditions, yet many of our biocontrol agents may lack the genetic diversity needed for effective adaptation.

Meanwhile, warming in the north will open up opportunities for new crops, with their associated pests and diseases. National, inter-island, and local biosecurity are likely to be increasingly important for managing the associated risks.

A common observation by those participating in this project was our lack of ecological knowledge of the biocontrol systems that are working. Given this information is essential in planning IPM and IFM systems that will protect our productive sectors in the future, there is a chance some crop systems may be caught by surprise.

There is a need for decision makers in government, industry and iwi to understand the wider issues in maintaining effective biocontrol systems in the face of change and recognition given to the type of information needed.

7.   Planning for the future

The gradual pace of climate change allows industry and land managers the time to implement strategies that will ensure biocontrol continues as a mainstream pest management tool in the productive and environmental sectors. These could include:

- **Refuge habitats**

The provision of habitats within the agricultural landscape that support a high abundance and diversity of predators and parasitoids should provide a buffer against the perturbations of extreme weather events. Implementation of conservation/revegetation programmes can increase the range of microclimates available to natural enemies and enhance their survival and efficacy by providing protection against the elements, sites for overwintering or aestivation, and resources that encourage synchrony with target hosts (nectar, pollen and alternative hosts for generalist species).

- **Pre-emptive action against sleeper pests**

"Sleeper pests" are species already in New Zealand but kept in check by factors such as host/habitat unavailability and low temperature. Potential biological control solutions should be pre-emptively investigated for those that are likely to become serious pests under climate change, and for which effective biocontrols are available overseas. Such programmes can be relatively inexpensive to transfer to New Zealand. Where the potential for biocontrol appears poor, then alternative management plans should be developed. These may range from good quality surveillance and local eradication/management to crop protection strategies such as plant resistance.

- **Risk management for IPM/IFM systems**

Existing IPM/IFM systems should be reviewed and areas at greatest risk from climate change in each system identified. It is likely that large knowledge gaps will become apparent and will need to be addressed. Increased understanding of the ecological requirements and dispersal ability of the key species suppressing pest abundance would assist in developing strategies to minimise the risk of pest outbreaks. In some cases, biocontrol agents may need to be physically transferred to crops being established in new regions.

- **Increased genetic diversity**

The capacity for current and potential biocontrol agents to adapt to climate change may be compromised when their genetic resources are limited. The genetic variability of populations of key biocontrol agents should be assessed, and, where necessary, the potential to introduce additional genetic stock should be evaluated. With the species already present in New Zealand, Environmental Risk Management Authority approval would not be required except in the cases of conditional approvals. However, new ecotypes could differ in host specificity and still should be tested.

- **Biosecurity and surveillance**

New exotic species pose a major risk and climate change will increase the risk that some of the frequent subtropical "door knockers" arriving by wind or human transportation will come permanently established. Apart from being possible new pests, they have the potential to disrupt existing IPM/IFM systems, displacing currently effective biocontrol agents or directly attacking the biocontrol agents (e.g. hyperparasitoids). Border biosecurity and surveillance in at risk localities, backed by rapid response, are the major defences.

- **Modelling**

Predictive models may suggest where, when and how biocontrol systems might fail under future climate change scenarios. Conversely, they may also suggest localities where a particular system would work best, which may be of relevance when planning long-term plantings such as orchards, vineyards, forests and urban amenities. Modelling can also be used to highlight key times in the season that a biocontrol system could be augmented or manipulated to improve control. This could include the use of pesticides/biopesticides, the introduction of a new natural enemy, resource provision, and the optimal timing and sequence of crops in a district. However, since models are only as good as the data they summarise, there will be an ongoing need for robust research.

- **Grower awareness**

Each of the actions suggested above relies on support, awareness and communication with and between farmers, growers and other land managers. Growers need to be aware of how climate change may affect the outcomes of their biocontrols so that they can plan, monitor and adjust their management practices appropriately. Growers may have an especially important role in early detection of problems, and in validating the predictions from models.

It is worth highlighting as a final point that climate change is not just a phenomenon of the future: it has already been occurring for several decades. We are already well along the track from the baseline climate assumed in the above analyses towards the 2040 (2030 to 2049) predictions from section 2.2. New Zealand's biocontrol systems are already reacting to climate change, so management cannot be premature.

8. Acknowledgements

9.   References

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10 Appendices

10.1 Participants at the workshop on impact of climate change on biocontrol in New Zealand

Chair: Travis Glare, Lincoln University

AgResearch
- Pip Gerard (organiser)
- Barbara Barratt
- Craig Phillips
- Trevor Jackson
- Sue Zydenbos (scribe)

Plant & Food
- John Charles
- Garry Hill
- Graham Walker

Scion
- Toni Withers

Landcare
- Simon Fowler
- Lynley Hayes

NIWA
- Andrew Tait

Lincoln University
- Sue Worner

Northland Regional Council
- Jenny Dymock

ERMA
- Geoff Ridley
- Linda Faulkner