Future-proofing food: striving towards minimal insecticidal application in Western Cape pome fruit orchards

by
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Declaration

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Summary

Increasing pressure on food production and the concern over maintenance of biodiversity and ecosystem services is creating an urgent need to future-proof food production, while maintaining the natural environment for future generations. Within the Cape Floristic Region (CFR) biodiversity hotspot in the Western Cape of South Africa, deciduous fruit is widely grown, contributing significantly to the local economy. To ensure access is maintained to important export markets, this study reviews the current available pest control options with focus on techniques able to preserve the biodiversity of the CFR, while simultaneously providing effective control over arthropod pests in pome fruit. A scenario planning technique is then used to depict potential future scenarios and the options we have in dealing with them.

Emphasis here is placed on economically important arthropod species, particularly Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) and codling moth *Cydia pomonella* (L.). Biological control (biocontrol) is discussed in detail, covering predators, parasitoids and pathogens. Biocontrol is an important, sustainable pest control measure. However, certain risks associated with releasing living organisms into the environment must not be ignored. Monitoring of release programmes is essential. The sterile insect technique (SIT) offers a species-specific approach to controlling pests. However, the technique is research and management intensive. Globally SIT has shown great success, but lack of financial support has limited SIT uptake locally. SIT has shown increased effectiveness as an integrated technique, particularly with parasitoid release and pheromone-based mating disruption. The management of orchards as agroecosystems shows that preservation of natural vegetation and beneficial plant species increases crop resilience, encourages conservation biological control and maintains crop health. The importance of area-wide control is discussed under each section, as a favourable strategy which deals with entire pest populations rather than isolated farm-by-farm approaches. Other techniques covered include pheromone-based mating disruption, attract-and-kill and physical barriers such as sticky tree-bands, which all show integration potential with biologically-based techniques while minimising insecticide application. The usefulness of insecticides as a curative approach is recognised, and ways of preserving insecticide life-spans by limiting insecticide resistance are discussed.

Social, economic, political, environmental and technological driving forces are used to develop four realistic future scenarios for pome fruit production in the CFR. The scenarios are based on the extremes of two key uncertainties: development of resistance to chemical insecticides, and changes in legislation regulating insecticide usage. The options we face in dealing with each potential scenario, with the suite of arthropod pest control techniques currently developed, is discussed. It is hypothesised that a best-case scenario, in which environmentally-friendly techniques which support healthy, productive agroecosystems, can be reached. We should carefully assess our options, and begin to shift pest control from a predominantly chemical basis to one in which habitat management and biocontrol form the basis of control, with techniques such as SIT, mating disruption and physical barriers assisting in creating holistic arthropod pest control systems. In light of the uncertainty that the future holds, a scenario planning exercise such as this, can assist in decision making today that will best prepare us to deal with future threats such as climate change and new pest invasions.

Opsomming

Toenemende druk op voedselproduksie en kommer oor die handhawing van biodiversiteit en ekosisteemdienste lei tot ‘n dringende behoefte om voedselproduksie toekoms-bestand te maak, asook om tegelykertyd die natuurlike omgewing vir toekomstige generasies te bewaar. Binne die Kaap Floristiese Streek (KFS) ‘biodiversiteitskern’ in die Wes-Kaap van Suid-Afrika word sagte vrugte algemeen verbou en lewer ‘n aansienlike bydrae tot die plaaslike ekonomie. Om toegang tot belangrike uitvoermarkte te verseker ondersoek hierdie studie die plaagbeheer opsies tans beskikbaar, met die fokus op tegnieke wat die biodiversiteit van die KFS kan bewaar en tegelykertyd effektiewe beheer oor geleedpotige plae van kernvrugte kan verskaf. ‘n Scenario-beplannings-tegniek word dan gebruik om moontlike toekomstige scenario’s en die opsies tot ons beskikking om hulle te hanteer, uit te beeld.

Klem word hier geplaas op geleedpotige spesies van ekonomiese belang, veral die Mediterreense vrugtevlieg, *Ceratitis capitata* (Wiedemann) en die kodlingmot *Cydia pomonella* (L.). Biologiese-beheer (biobeheer) word in diepte bespreek, en dek predatore, parasiete en patogene. Biobeheer is ‘n belangrike, volhoubare plaagbeheer-middel; alhoewel sekere risiko’s verbonde met die vrystelling van lewende organismes in die omgewing nie verontagsaam moet word nie. Dit is noodsaaklik dat vrystellingsprogramme gemoniteer word. Die steriele-insek-tegniek (SIT) bied ‘n spesies-spesifieke benadering tot die beheer van plae, alhoewel dit navorsings- en bestuursintensief is. SIT het wêreldwyd al groot suksesbehaal, maar ‘n tekort aan finansiële ondersteuning het die plaaslike toepassing van SIT beperk. SIT het verhoogde effektiwiteit as ‘n geïntegreerde tegniek vertoon, veral met die verlies van parasiete en feromoon gebaseerde parings-ontwrigting. Die bestuur van boorde as agro-ekosisteme wys dat die bewaring van natuurlike plantegroei en voordelige plant spesies oes-herstelvermoë verhoog, bewaring-biologiese-beheer aanmoedig en oes-welstand handhaaf. Die belang van streekswye beheer word bespreek onder elke afdeling as ‘n gunstige strategie wat te doen het met algehele plaagbevolkings, eerder as afsonderlike plaas-tot-plaas benaderings. Ander tegnieke wat gedek word sluit in feromoon gebaseerde parings-ontwrigting, lok-en-doodmaak en fisiese versperrings soos taai boom-bande, wat alles integrasie-potensiaal wys met biologies gebaseerde tegnieke en tegelykertyd insekdoder aanwending verminder. Die nuttigheid van insekdoders as ‘n herstel benadering word erken en maniere om die leffektiwiteit van insekdoders te behou deur insekdoder-weerstand te beperk, word bespreek.

Sosiaal-, ekonomies-, polities-, omgewings- en tegnologies-gedrewe kragte word gebruik om vier realistiese toekomstige scenario’s vir kernvrug-produksie in die KFS te ontwikkel. Die scenario’s is baseer op die ekstreme van twee belangrike onsekerhede:

ontwikkeling van weerstand teen chemiese insekdoders, en veranderinge in wetgewing wat die gebruik van insekdoders reguleer. Die opsies wat ons in die gesig staar om elke potensiële scenario te hanteer met die verskeidenheid van geleedpotige plaagbeheer-tegnieke tans ontwikkel is, word bespreek. Dit word veronderstel dat ‘n beste scenario, waar omgewings-vriendelike tegnieke wat gesonde, produktiewe agro-ekosisteme onderhou, bereik kan word. Ons moet ons opsies versigtig assesseer, en begin om plaagbeheer vanaf ‘n oorwegend chemiese basis te skuif na een waar habitat-bestuur en biobeheer die basis van beheer vorm, en waar tegnieke soos SIT, parings-ontwrigting en fisiese versperrings help om holistiese geleedpotige-plaagbeheer sisteme te vorm. In die lig van die onsekerheid wat die toekoms inhou, kan ‘n scenario-beplannings oefening soos hierdie besluitneming vandag aanhelp wat ons die beste sal voorberei vir die hantering van toekomstige bedreigings soos klimaats-verandering en nuwe en vreemde plaag-indringing.

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Contents

1) General Introduction

The reality facing Planet Earth is that the human population is growing, and the land available for agricultural development is becoming scarce (Alexandratos 1999; Borlaug 1997; Cunningham *et al.* 2013; FAO 2006). The ever-increasing number of mouths to feed has resulted in the large-scale commercialisation and intensification of agriculture, with increased reliance on mechanisation and chemical inputs, since the agricultural revolution after the Second World War (Buttel 1993; Perkins & Holochuck 1993). In South Africa, profitability of farms has decreased and many small-scale farms have been bought out by larger commercial farms (DAFF 2014). Unfortunately, these intensified farming practices have spin-offs on surrounding areas, which can be harmful to wildlife and the environment, not to mention human health (Carson 1962).

In a World with finite resources, it is essential to balance food production with the protection of our natural environment. The seventh Aichi Target states: ‘By 2020 areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity’ (CBD 2010). This necessity for sustainable agriculture is slowly becoming recognised, and with the aid of international conservation targets, food production may be able to meet the demands of the growing human population (Altieri 1995; Cunningham *et al.* 2013; Godfray *et al.* 2010).

A series of events formed part of what can be called the agrochemical revolution. During World War II (WWII), nitrate production greatly increased and productivity on farms benefited immensely due to the decreased price of fertiliser (Buttel 1993). During the same period, the emergence of the organochlorine DDT occurred as a ‘wonder-chemical’ in protecting soldiers from typhus fever and malaria in the tropics (Simmons 1945). The great success of DDT resulted in a widespread search for new synthetic organic insecticides, which would subsequently replace the inorganic compounds (for example, lead arsenate) that were predominantly being used in agriculture (USDA 1953). For several years post WWII, synthetic organic pesticides such as the organic chlorines and organic phosphates dominated arthropod pest control (Osteen 1993). Pesticide usage continued to grow until the early 1980s when the markets began to saturate (Osteen 1993). The growth of the agrochemical industry occurred at a time when labour was relatively expensive (Buttel 1993), thus mechanisation was an alternative and coupled with chemical inputs, farm specialisation occurred resulting in fewer, larger farms (Perkins & Holochuck 1993; Rosset & Altieri 1997).

As a result of this specialisation of farms and an ever growing agrochemical industry, growers were at a competitive disadvantage if they did not engage in the use of cheap nitrogen fertilisers (Cochrane 1979). Agriculture had thus become an industry aimed at maximising profits by selling goods to markets, not just a means of growing food for a surrounding community (Perkins & Holochuck 1993; Pingali & Rosegrant 1995).The impact of this meant that any losses of crop due to damage by pests were reflected in a farmer's income (Perkins & Holochuck 1993).

Commercialised farmers were aiming to control pest outbreaks in the cheapest and most effective way possible. Entomology and ecological sciences had taken a back seat at this period as the agrochemical industry had stolen the limelight with the efficiency of the cheap, synthetic organic pesticides (Buttel 1993). Cultural, physical and biological methods of pest control were all established, but in order to remain competitive, it was more appealing for farmers to use the quick-fix option of chemical control (Ehler 2006). Increases in yields were experienced thanks to the effective pest control measures provided by insecticides, coupled with increased fertiliser inputs, improved irrigation systems and new strains of crops (Cooper & Dobson 2007; Warren 1998).

After about ten years of insecticide usage, resistance to the compounds was already arising in arthropod populations (Carson 1962). Pesticide usage increased exponentially from the 1950s to the 1980s, but interestingly, the amount of crop damage due to arthropod pests nearly doubled in that time (Altieri 1995; Osteen 1993). Generally new chemical compounds, or mixtures of insecticides, are used to combat resistant arthropod populations. However, what tends to happen, and is still happening today, is an example of the 'Red Queen Hypothesis' and is known as the pesticide treadmill (Van Den Bosch 1989). The Red Queen in Lewis Carroll's *Through the Looking-Glass, and What Alice Found There* (Carroll 1871) states, "Now, here, you see, it takes all the running you can do, to keep in the same place". Insecticide producers must 'keep running' and continuously develop new formulations of chemicals in order to continue to control ever-evolving, resistant arthropod pest populations.

Not only did arthropods quickly develop resistance to insecticides, but the widespread environmental effects and disruption of non-target organisms was soon apparent (Altieri 1995). Early signs of the detrimental effects of certain synthetic compounds were made obvious to the public during the mass spraying campaigns of the 1950s in the USA to control Dutch elm disease, gypsy moth, Japanese beetle and the fire ant (Carson 1962). Aerial sprays covered agricultural areas, towns and parks with chemical dust. Within a few days of spraying, dead birds were found in peoples' gardens and along roadsides after ingesting poisoned insects (Carson 1962). Residues of these chemicals threatened other wildlife, as well as human safety and as a result public outcries ensued.

A turning point in the history of pesticide usage occurred in 1962 when Rachel Carson released the book *Silent Spring*. Huge controversy was sparked as chemical companies along with government agencies who promoted these chemicals were now under a negative spotlight. Opinions were divided as certain people supported Carson's views, while others felt that the benefits of using pesticides greatly outweighed the costs (Dunlap 2008). Above and beyond, what Carson achieved was public awareness of the chemicals being used regularly and recklessly (Dunlap 2008). This was an essential step in the environmental movement that revived the search for alternative pest control measures and focused science back on to ecology, emphasising its value in agricultural systems.

The term Integrated Pest Management (IPM) was first used formally in the late 1960s in a report by the US National Academy of Sciences (NAS 1969). IPM evolved over several years as a means of controlling crop pests in ways that are more sustainable in terms of agroecology and the environment. IPM has been defined in many ways over time (see Bajwa & Kogan 2002). Essentially, IPM aims to limit economic damage of pests on crops while simultaneously minimising effects on non-target organisms, the environment and human health. This can be achieved only with thorough knowledge of the pests involved, as well as the dynamics of the local environment and the fauna and flora therein.

IPM is an *integrated* approach as many control techniques are incorporated that must complement each other. Control techniques can be physical, physiological, biological, cultural, or chemical. Chemical control is used selectively and with caution so as to not affect natural enemies, but is not at all ruled out of IPM. *Pest* refers to any organism that could potentially cause economic damage to the crop. This usually denotes to arthropods but includes vertebrate pests as well. *Mangament* refers to the necessity for research and understanding of the agroecosystem as well as consistent monitoring of potential pest populations along with long-term plans. IPM theory is vast, however its uptake in the field has been limited, partly due to the widespread reliance of commercial farmers on insecticides (Altieri 1995; Dent 2000).

An important aspect of IPM, is the utilisation of monitoring of pest populations in order to make management decisions. Certain thresholds are outlined, which define at what level a certain pest population would require intervention to inhibit economic damage from arising (Stern *et al*. 1959). The three thresholds outlined include 1) The economic injury level (EIL), which indicates the lowest pest population level that will cause damage of economic significance, 2) the economic threshold (ET), which indicates the pest population level at which control measures should be applied to prevent the EIL from being reached and economic damage from occuring and 3) the economic damage level (ED), is the level of economic damage at which the costs of pest population control are justified (Stern *et al.* 1959).

An issue faced by the traditional farm-by-farm IPM approach is that implementation on a localised basis is inadequate in providing sustained, long-term control over arthropod pests (Vreysen *et al.* 2007). When only localised pest populations are managed, untreated sources such as neighouring farms, home-gardens and other suitable tracts of vegetation can harbour source-populations of arthropod pests, which can reinvade agriculural areas causing growers to turn to quick-fix control options, usually insecticides (Lewis *et al.* 1997). A more effective and sustainable solution is to target entire populations of insects, especially in geographically isolated areas (Hendrichs *et al.* 2007). The area-wide IPM (AW-IPM) approach is favourable in terms of pest management, as entire populations are controlled, limiting the refuge populations that would have caused damage to agricultural areas under a farm-by-farm IPM approach. AW-IPM can also be an effective insecticide resistance management technique, if suitable control measures are applied. The challenge in implementing AW-IPM is to gather funding for large scale implementation of pest control, often over non-agricultural areas, and to form collaborations between all growers, normally of different scales and crop varieties, in an entire area (Hendrichs *et al.* 2007).

The Cape Floristic Region (CFR) forms a large part of the Western Cape of South Africa (Manning 2008). The CFR, one of the world's biodiversity hotspots, boasts some 9000 plant species of which nearly two-thirds are endemic (Manning 2008). The Western Cape not only plays home to a large array of biodiversity, but also offers optimal growing conditions for deciduous fruit (Provincial Development Council 2005). Some of the world's top wine estates are found here, while an array of other fruit crops are grown. Pome fruit prouction adds a significant proportion of income to the local economies, with roughly 22 000 hectares of apples planted in the Western Cape alone (HortGro 2013). Pome fruit produce is primarily exported, of which the majority is sent to the UK and other African countries (HortGro 2013).

In order for exports to remain competitive, strict phytosanitary requirements need to be met, or exports face being rejected, with growers suffering economically. Not only must phytosanitary requirements be met, but consumers are becoming more and more aware of the environmental degradation that is occurring, as well as the health risks associated with agrochemicals. To emphasise this, the major supermarket chain Sainsbury's in the UK has developed a '20 by 20 Sustainability Plan'. Sainsbury's chief executive Justin King states: "Through our 20 commitments we want to change the retail industry so that it can sustain the natural world, meet our customers' demands and promote health and wellbeing" (Sainsbury's 2013). On South African soil, Woolworths and the World Wide Fund for Nature (WWF) have collaborated and developed 'Farming for the Future' (King & Thobela 2014). This collaboration outlines the retailer's commitment to providing consumers with produce that conforms with environmental best-practice and fair trade, ensuring that consumers are able to purchase food that is not only healthy for humans, but that has also been produced in an environmentally-friendly manner.

A shift has been taking place, from reliance on external inputs, to the realisation that agricultural systems need to become more self-reliant in order to remain sustainable (Altieri 1995). With pressure to feed a growing population, agricultural intensification and expansion threaten biodiversity conservation (Cunningham *et al.* 2013). In the Western Cape, it is essential that production of food and conservation of biodiversity are prioritised together, and not treated in isolation, as large tracts of the vulnerable CFR are split into a mosaic of natural fynbos and agricultural land. Monocultures and the inputs required to sustain adequate production have been associated with lower species diversity (Gaigher & Samways 2010; Witt & Samways 2004) and other negative environmental spin-offs such as eutrophication (Kleijn *et al.* 2009).

In light of the uncertainty that the future holds, it is in our best interest to prepare accordingly, so that whatever situation arises, we will be able to thrive (Ilbury & Sunter 2011). Future-proofing our food supply is one such demand that must be met in the future. Threats such as new pest invasions, climate change, and increasing demand for healthier and more environmentally-friendly agricultural practices (Hulme 2009; Midgely & Lötze 2008) need to be considered along with important conservation targets such as the Aichi Targets (CBD 2010). To prepare for such threats and demands, while maintaining market access to valuable overseas markets, the current arthropod pest control situation must be reviewed in Western Cape pome fruit industries.

At present, economically significant pests in Western Cape pome fruit orchards include codling moth *Cydia pomonella* (L.), Mediterranean fruit fly *Ceratitis capitata* (Wiedemann), Natal fruit fly *C. rosa* (Karsch) and banded fruit weevil *Phlyctinus callosus* (Schöenherr). Other pests may sporadically cause extensive damage, but it is the control of these above-mentioned pests that require most control effort (K. Pringle, pers. comm.). Insecticides are still the dominant method of controlling these pests, and as a result, resistance to the chemicals remains a key issue, not to mention environmental and human health concerns, as well as the pressure to remain within local and international regulations set for chemical insecticide usage (HortGro 2014; IRAC 2014; King & Thobela 2014). To effectively deal with these and other pests of economic significance, there is a need for more environmentally-friendly, area-wide pest control techniques to be implemented in Western Cape pome fruit production.

The purpose of this study is to answer two pertinent questions relating to arthropod pest control in Western Cape pome fruit production:

1) Where are we now?
2) Where do we choose to go from here?

This thesis is separated into two main sections. Part one deals with question 1) and aims to outline all the available pest control techniques in pome fruit at present, including biological, physical, cultural, physiological and chemical forms of pest control. Each chapter reviews the literature from local and interantional examples of relevant application of the control techniques in the field, and relates the principles to the situation of the Western Cape pome fruit industry. Part two of this thesis aims to answer question 2) by introducing a technique known as *scenario planning* in which the information gathered in the first part of the thesis is assessed in a structured manner, to draw up potential future scenarios for the industry.

Scenario planning is an intuitive and creative way of utilising facts and uncertain factors, that could drive changes in the way we operate, to assess what future possibilities may arise (Amer *et al*. 2013). By thoroughly deconstructing our current practices (in this case arthropod pest control) and the present environment in which we find ourselves, it is possible to generate a clearer picture of what the future may hold, in the form of alternate future scenarios. This is a useful way of preparing for whatever the future may hold, by shedding light on our current strengths and weaknesses. By reviewing the opportunities and threats we face in the long-term, we are able to choose the most appropriate agricultural practices and pest control techniques that can aid in leading us towards a sustainable food production system.

The driving forces and uncertainties for the Western Cape pome fruit industry will be discussed in the second part of this thesis and potential future scenarios developed according to the general probability and impact of these forces arising. From here, the aim is to discuss how these sceanrios would influence pest control in pome fruit, and what options we have as we head into the future. This more creative way of thinking brings together different disciplines to achieve a common goal. It is hoped that by introducing this novel method of analysing scientific literature, the gap between research and field implementation will be bridged.

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Where we are now: Outlining current arthropod pest control options in Western Cape pome fruit orchards

Thesis Part One

2) A review of biological control options for arthropod pests in Western Cape pome orchards

ABSTRACT

Biological control is an important component of agricultural integrated pest management. However, broad spectrum insecticides can inhibit the ability of natural enemies to suppress pest species. Due to pressure for more environmentally- and health-friendly pest control techniques, it is necessary to review what options are available. This study categorises pests into four groupings: non-pests, sporadic pests, perennial pests and chronic pests. The key arthropod pests of apples in the Western Cape of South Africa are discussed under their respective section in terms of biological control options. Biological control options include the use of natural enemies, parasitoids and pathogens (viruses, nematodes, bacteria and fungi). Emphasis is placed on economically important species, particularly the chronic pests, Mediterranean fruit fly *Ceratitis capitata* and codling moth *Cydia pomonella*. Biological control holds great promise to become the backbone of integrated pest management in Western Cape apple orchards. However to do so, the widespread use of broad scale chemical insecticides needs to be curtailed and integration with landscape scale habitat management and other environmentally friendly techniques needs to occur to provide conditions conducive to natural enemy survival and success. The risks of biological control must not be ignored and the importance of pre- and post-release studies and monitoring is highlighted here.

INTRODUCTION

Biological control (biocontrol) aims to utilise natural enemies of pests by introducing them (or augmenting the already occurring populations) into an agricultural system in an effort to control pest populations (Dent 2000). Biocontrol rarely eradicates the pest population but rather controls the target pest population level, keeping the agricultural economic damage at a level to prevent the economic threshold from being reached (Gullan & Cranston 2010). Biocontrol agents can be separated into three main functional categories: predators, parasitoids and pathogens. Predators are generally larger than prey and capture and consume their targets. Examples of predatory insects include, for example, neuropteran larvae and ladybird beetles (Coccinellidae). Parasitoids are smaller than their host and spend part of their lifecycle in the host, usually killing it. Pathogens include any agents that cause disease, notably bacteria, viruses, fungi and nematodes.

Biocontrol by natural enemies can differ on annual versus perennial crops (*e.g.* herb fields *versus* pome fruit orchards). In perennial systems, natural enemies are able to remain in the agricultural system from one year to the next and are intended to suppress pest populations if or when the population rises to economically damaging levels. In annual crops, there is often not sufficient habitat within which natural enemies can remain and prey population numbers will fluctuate due to less variation of habitat for prey species (Samways 1981).

The use of certain chemical pesticides can negatively influence indigenous natural enemies of pest species, disrupting the suppressive effect of natural enemies on pest populations (Samways 2005). In order to effectively suppress insect and mite pest populations to acceptable levels, in an environmentally-friendly manner that allows for crop production alongside the protection of the environment and human health, alternatives to chemical pesticides are required. Biocontrol is one of these alternatives that are often investigated as a component of Integrated Pest Management (IPM) systems in, for example, pome fruit production.

In the deciduous fruit production area of the Western Cape of South Africa, a suite of different pest species pose constant threats to the commercial production of apple and pear fruit (DFPT, unpubl.). Apart from conventional chemical control methods, a number of alternative techniques are currently in use against certain pest species. One example is the area-wide sterile insect release programme that is currently underway against the Mediterranean fruit fly *Ceratitis capitata* (Diptera: Tephritidae) in the Elgin and Grabouw region of the Western Cape. Regarding biocontrol specifically, there are many natural enemies that have the potential to be used as control agents against many of the Western Cape pome fruit pest species. Against this background, the aim of this review is to investigate which biocontrol agents are currently being used against the major pest species of pome fruit in the Western Cape, and to focus on which agents have the potential to be efficacious against pome fruit pests in the future. Wherever possible, the review focuses on the specific pome fruit pests and their known control agents specifically in the Western Cape. However, global examples are also analysed here to generate a broader picture of biological control programmes. This review focuses on classical (utilising natural enemies from the pest's native region), inundative (releasing large numbers of natural enemies in relation to the pest), augmentative (supplementing already established natural enemy populations) and inoculative (releasing natural enemies into an area in which they do not occur in order to try and establish a population) methods of biocontrol, but omits conservation biocontrol.

SCOPE OF REVIEW

I gathered as much information as possible on past and present biocontrol programmes with focus on pome fruit production in the Western Cape. The following list of pest species were investigated (based on DFPT, unpubl.):

Lepidoptera

Noctuidae: African bollworm (*Helicoverpa armigera* (Hübner)); Tortricidae: codling moth (*Cydia pomonella* (L.)), apple leafroller (*Tortrix (=Lozotaenia) capensana* (Walker).

Coleoptera

Curculionidae: banded fruit-weevil (*Phlyctinus callosus* (Schönherr)), long-legged weevil (*Sciobius tottus* (Schönherr)), grey weevil (*Eremnus atratus* (Schönherr)); Chrysomelidae: fruit nibbler (*Prasoidea sericea* (Gyllenhal)).

Hemiptera

Aphididae: woolly apple-aphid (*Eriosoma lanigerum* (Hausmann)), spirea aphid (*Aphis spiraecola* (Patch)); Pseudococcidae: citrophilus mealybug (*Pseudococcus calceolariae* (Maskell)), long-tailed mealybug (*P. longispinus* (Targioni Tozzetti)), pear & apple mealybug (*P. viburni* (Signoret)); Diaspididae: pernicious scale (*Diaspidiotus (=Quadraspidiotus) pernicious* (Comstock)), red scale (*Aonidiella aurantii* (Maskell)); Pentatomidae: antestia bug (*Antestiopsis orbitalis* (Leston)).

Thysanoptera

Thripidae: western flower thrips (*Frankliniella occidentalis* (Pergande)), Common blossom thrip (*F. schultzei* (Trybom)).

Diptera

Tephritidae:
Mediterranean fruit-fly (*Ceratitis capitata* (Wiedemann)), Natal fruit-fly (*Ceratitis rosa* (Karsch)).

Acari

Tetranychidae: two-spotted mite (*Tetranychus urticae* (Koch)); red spider-mite (*Panonychus ulmi* (Koch)); bryobia mite (*Bryobia rubrioculus* (Scheuten))

SUMMARY OF INDIVIDUAL PEST SPECIES AND THEIR CONTROL

The physiology and behaviour of individual pest species determines what control measures need to be taken. Thus, it is necessary to discuss each of the major and secondary pest species individually to obtain an assessment of what are the current risks to pome fruit production, and what steps have to be taken to control these pests biologically. The pests have been categorised in terms of their general equilibrium position (GEP) and how this relates to the economic threshold (ET) and the economic injury level (EIL) (Stern *et al.* 1959).

The four categories are: Non-Pests; Sporadic Pests; Perennial Pests and Chronic Pests. Pringle (2006) gives a clear explanation of the parameters outlining each of the four categories, and these are illustrated in figure 2.1.

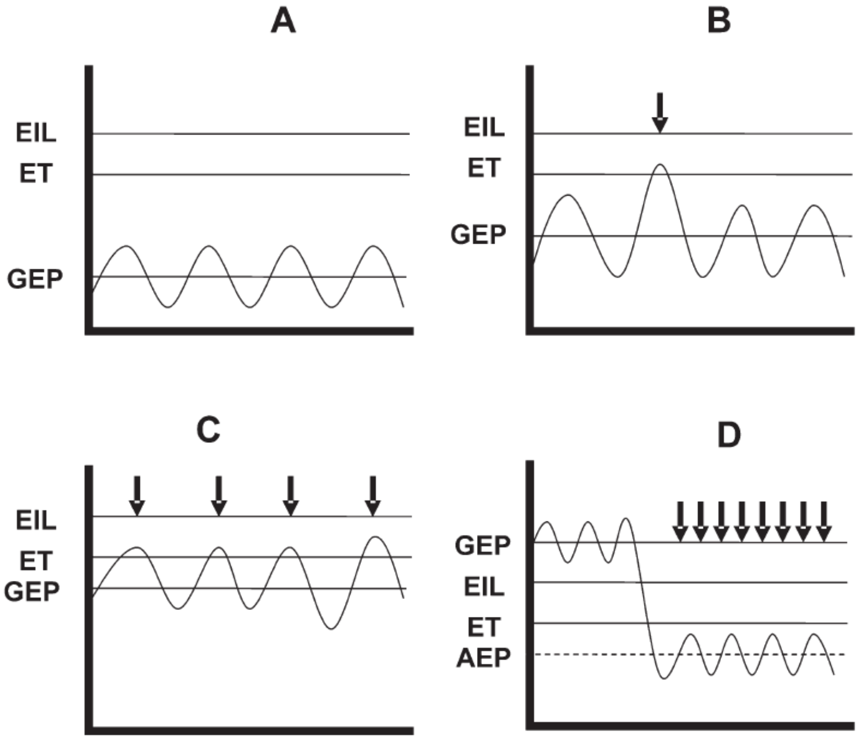

Figure 2.1: The four categories of pests: (A) non-pests, (B) sporadic pests, (C) perennial pests and (D) chronic pests. EIL= economic injury level, ET= economic threshold, GEP= general equilibrium position and AEP= adjusted equilibrium position. From Pringle (2006).

Non-Pests

These species may occur in the orchards and may feed on the trees, but the GEP of the population always remains below the ET (Stern *et al.* 1959). (Figure 2.1A)

Two-spotted spider mite (*Tetranychus urticae*) and European red mite (*Panonychus ulmi*)

The mite species *T. urticae* and *P. ulmi* can both cause damage in Western Cape pome fruit orchards (Pringle 2006). They are considered as non-pests in certain areas (Elgin- Grabouw area), but perennial in others. Non-pests would not normally require much attention. However, the use of pesticides may cause non-pests to rise in status to a level that may be of economic concern. This is because primary pests may be taken out of the system, leaving a niche open for secondary pests to exploit, thus allowing them to increase in numbers. This was the case with the early use of DDT and the severity of *T. urticae* outbreaks in the Western Cape (Kriegler 1960).

These two mite species are currently under satisfactory control by natural enemies (both naturally occurring and introduced) present in orchards (Pringle 2001). Mite control previously relied on an intensive acaricide programme, which has now been curtailed (Pringle 2001). In 1989, the predatory mite *Galandromus (=Metaseiulus) occidentalis* was introduced into orchards in the Western Cape specifically for control of *T. urticae* and *P. ulmi*. Biological control by *G. occidentalis* was not sufficient to successfully control mite numbers without chemical intervention, and thus acaricide applications were necessary. Releases of *G. occidentalis* were stopped and the predator has subsequently not been able to survive in the orchards without supplementary releases. Another predator, *Neoseiulus californicus*, was unintentionally introduced into apple orchards in Elgin and was first recorded in the 1994/1995 growing season (Pringle 2001). This has since allowed for the reduction in acaricide applications and, along with other predatory mites such as *Phytoseiulus persimilis* (Athias-Henriot) and *Euseius addoensis* (McMurtry), is providing sufficient control of *T. urticae* and *P. ulmi* (Pringle 2001).

Pringle and Heunis (2006) determined the benefit:cost ratio of the biological control of phytophagous mites in Elgin when using *N. californicus*. Acaricides should not be used below a 40% leaf infestation, and, to ensure maximum effectiveness of biological control by *N. californicus*, acaricides should not be applied before 80% leaf infestation. As the predatory mites were unintentionally introduced, initial costs of biological control were non-existent and the benefit:cost ratio was calculated to be 189.4:1 if one acaricide spray was saved at an average cost of R250/ha at the time of the study (2003/2004).

Certain predatory mites (*N. californicus* and *E. addoensis*) are able to feed on other food items such as pollen and thrips, and in combination with mite prey can lead to effective year-round suppression of *T. urticae* and *P. ulmi* (Pringle 2001). Croft and Macrae (1992) found that the combination of *G. occidentalis* and the predatory mite *Typhlodromus pyri*

(Scheuten) was more effective at controlling *T. urticae* and *P. ulmi* than either predator alone, indicating a synergistic relationship. The presence of cover crops is important to ensure the longevity of the predatory mites in orchards by providing an alternate source of food in the form of pollen and other non-pest insect prey that live on the cover crops.

Organophosphate-resistant predatory mites have been used in apple orchards in the United Kingdom, and are released alongside specific chemical insecticide applications for other pests without being harmed (Solomon *et al.* 1993). These strains may be useful to breed and be available for inundative release should the pest phytophagous mite populations ever reach damaging levels, rather than utilising harmful chemical acaricides.

One case of suspected ‘resistance’ by *T. urticae* to biological control by *Phytoseiulus persimilis* was reported in a commercial cut-rose plantation in California (Redak & Bethke 2008). The apparently resistant mites were removed and tested in a laboratory for any genetic signs of resistance. The endoparasitic bacterium *Wolbachia* was also investigated within each of the mites, but no influence was found. It was concluded that the reported resistance was in fact not actual genetic resistance, and that poor management along with sub-standard monitoring practices allowed for the pest population to rise to high levels. These high levels of *T. urticae* were above the level at which standard releases of *P. persimilis* were effective, and thus control was no longer sufficient (Redak & Bethke 2008). Regular monitoring and efficient sampling methods are needed to ensure that this sort of issue does not occur in other areas.

Future considerations in the management of mite pests could consider the use of Volatile Organic Compounds (VOCs) in orchards. VOCs are compounds that are released into the air by plants as a result of herbivory. They are sometimes targeted specifically at the co-occurring natural enemies of the pests that may have induced VOC release (Sutherland 2010), resulting in a symbiotic relationship between plant and predator, whereby plants gain protection and predators gain access to prey. Llusia & Penuelas (2001) found that when apple trees are attacked by phytophagous mites, including *P. ulmi*, trees released VOCs. The predatory mites *Amblyseius andersoni* (Chant) and *N. californicus* were found to be attracted to the VOC signals with 85% of released predators going to branches infested with *P. ulmi* and 15% going to uninfested branches. There is potential to isolate these chemicals and utilise them as an addition to insecticide applications to ensure that infested trees are targeted by released predatory mites.

Other species

Two other species that have caused economic damage in the past, but are currently not causing damage at present include spirea aphid (*Aphis spiraecola* (Patch)) and the apple leaf roller (*Lozotaenia capensana* (Walker)). These two species could potentially cause economic damage in the future if the natural balance is disturbed and are thus worth noting. For example, *L. capensana* became a problem after DDT was introduced into South Africa, because the parasitoids that controlled it were destroyed, while the pest itself was not (Basson & Myburgh 1960). If new chemical complexes are introduced, there is the possibility of secondary pest outbreaks occurring again.

Sporadic Pests

These species have a GEP that is below the ET for most of the time. At certain periods however, the GEP may increase to a level above the ET, requiring control of the pest population (Stern *et al.* 1959). (Figure 2.1B)

DFPT (unpubl.) lists 14 sporadic pests on apples and pears in South Africa. The two species of primary concern are banded fruit weevil (*Phlyctinus callosus* (Schönherr)) and African bollworm (*Helicoverpa armigera* (Hübner)). Along with these two species, the following sporadic pests are also considered here: Citrophilus mealybug (*Pseudococcus calceolariae* (Maskell)); long tailed mealybug (*P. longispinus* (Targioni Tozzetti)); antestia bug (*Antestiopsis orbitalis* (Leston)); Western flower thrips (*Frankliniella occidentalis* (Pergande)); common blossom thrips (*F. schultzei* (Trybom)); fruit nibbler (*Prasoidea sericea* (Gyllenhal)); grey weevil (*Eremnus atratus* (Schönherr)); long legged weevil (*Sciobius tottus* (Schönherr)); apple leaf roller (*Lozotaenia* (=*Tortrix*) *capensana* (Walker)) and bryobia mite (*Bryobia rubrioculus* (Scheuten)).

Banded fruit weevil (*Phlyctinus callosus*)

The banded fruit weevil feeds directly on the apple fruit and can cause extensive damage. Myburgh *et al.* (1975) attributed 40% of all damage by pests on apples in the 1970s to *P. callosus*. There seems to be limited documented control over *P. callosus* using natural enemies. However, there is interest in the use of nematodes (Ferreira & Malan 2013) and fungal agents (Prestidge & Willoughby 1990) as control agents of the pest.

The nematode species *Heterorhabditis zealandica* (Poinar) was used by Ferreira and Malan (2013) against *P. callosus*. Mortality was in a wide range from 41-73% in larvae and 13-45% in adults. The limiting factors of utilising nematodes are their sensitivity to desiccation (Wright *et al.* 2005), as well as their temperature tolerance (Ferreira & Malan 2010). It was concluded that optimum control over *P. callosus* is achieved when nematodes are applied during winter and early spring, as at this stage, the larvae are present in the soil, which is when they are most susceptible to nematode attack. Optimum temperatures would be between 18 and 30°C as the nematodes are inactive below 15°C in the soil (Ferreira & Malan 2013).

Wit *et al.* (1995) investigated the use of helmeted guinea fowl (*Numida meleagris* (L.)) as a control agent against *P. callosus* in Elgin orchards. They found that the weevil was most numerous in plots where guinea fowl did not occur. However, the guinea fowl did not significantly reduce weevil numbers in the orchards. The fact that guinea fowl are diurnal, whereas the weevil is nocturnal may enable the weevil to avoid predation, even though guinea fowl tend to scratch and search for prey. The results of this study hold mixed outcomes for the use of vertebrates as biological control agents, as guinea fowl had a negative impact on overall invertebrate abundance and diversity. This was attributable to its general diet preference, as well as its impact on the cover crops between rows. Birds such as guinea fowl may hold value in reducing numbers of insects at low to moderate population numbers, but cannot be relied on for effective and selective pest control (Wit *et al.* 1995).

The use of fungi in conjunction with nematodes as control agents of *P. callosus* was successful in New Zealand (Prestidge & Willoughby 1990). Fungal pathogens such as *Metarhizium anisopliae* (Sorokin) are very effective in controlling insect pests, including *P. callosus*. The spores can be applied to the soil via the irrigation system when the weevil is in its larval stage, allowing it to be infected and killed before reaching adulthood. The spores are also able to be applied as a spray alongside insecticides, effectively killing adults as well. Spores are susceptible to UV exposure and are thus most effective in the soil (J. Kuiper, pers. comm.). The integration of nematodes and fungal pathogens, which are both effective in the soil against *P. callosus*, hold the most potential for future control of this pest species.

African bollworm (*Helicoverpa armigera*)

Limited studies have been conducted on the biological control of *H. armigera*, especially in pome fruit orchards. According to Pringle (unpubl.), bollworm caused an average of about 1.6% damage for the 2013/2014 growing season on Geelbos farm. This has been roughly the same since 2007, but in 2006/2007 the damage was up to an average of 19.4%, showing the potential of *H. armigera* to cause extensive damage.

A virus known as *Helicoverpa armigera* nucleopolyhedrovirus (HaNPV) has been used in several countries worldwide and has recently been brought into South Africa for use on several crops (Joubert 2012; Madumbi Sustainable Agriculture 2014). Although it is not yet registered for use on apples, it is specific to the *Helicoverpa* genus and thus has no effect on non-target organisms (Madumbi Sustainable Agriculture 2014). It showed great success on chickpeas in which a considerable reduction in pest density was observed, while crop yield was increased (Ahmad & Chandel 2004). Trials are underway in South Africa and have showed results in which peach fruit was 99% free of any damage when exposed to HaNPV (Joubert 2012).

Parasitoids of the genus *Trichogramma* have been the most effective egg parasitoids in controlling *H. armigera* in India (Romeis & Shanower 1996). These parasitoids are able to control the moths in the egg form and cause death before hatching (Alavo 2006). Indigenous parasitoid species in the genus *Trichogramma* should be investigated for use in IPM programmes for the Western Cape. Wahner (2008) found that the indigenous parasitoid *T. lutea* released to assist in the control of codling moth, also parasitizes *H. armigera*, an added benefit.

Alavo (2006) reviewed the biological control options for *H. armigera* and found that ants (Formicidae) and lacewings (Chrysopidae) are the most important predators for bollworm control. Much research has focussed on control of *H. armigera* in cotton, and studies have shown that predation by ants on bollworm eggs and larvae can be very high in the field (Mansfield *et al.* 2003). The mass rearing and release of ants and lacewings as biocontrol agents may be difficult logistically, and in the case of Western Cape orchards, most benefit would come from conserving and encouraging natural enemy populations that would assist in the control of bollworm in an IPM programme.

Mealybug species

*Obscure mealybug (*Pseudococcus viburni*) is in fact considered a perennial pest, but for ease of discussion, has been included here with the other mealybug species.*

Citrophilus mealybug (*Pseudococcus calceolariae*), long-tailed mealybug (*P. longispinus*) and obscure mealybug (*P. viburni*) all occur in Western Cape pome fruit orchards. Mealybugs have been difficult to control with chemical insecticides as they have cryptic lifestyles, often found behind bark or in crevices, rendering them largely unreachable by sprays (Walton & Pringle 2004). They also form resistance quickly, hence the need for alternate measures of control (Franco *et al.* 2009; Walton & Pringle 2004). Most research on biocontrol of mealybugs has focussed on specific hymenopteran parasitoid species of the family Encyrtidae (Bugila *et al.* 2014). Wakgari & Giliomee (2004) undertook a study on the natural enemies of mealybugs in the Western Cape and found five primary hymenopteran parasitoids, but no natural predators. One of the parasitoids is highly specific to *P. viburni* and is commercially available from the Netherlands (Charles *et al.* 2004).

It is believed that the use of chemical insecticides such as pyrethroids and organophosphates for the control of pests such as thrips, scale insects and lepidopterans are responsible for the resurgence of mealybug populations in orchards (Bedford 1997;

Hattingh & Tate 1997a; Hattingh & Tate 1997b). These insecticides are detrimental to the naturally occurring parasitoid complexes and natural enemies that normally keep mealybug populations under control (Van der Merwe 2000). Walton (2006) agrees with Wakgari & Giliomee (2006), reporting that there are few natural predators of mealybugs in Western Cape orchards. There is however, one ladybird, *Cryptolaemus montrouzieri* (Mulsant) (Coleoptera: Coccinellidae)), which is an effective mealybug predator in many countries which has been reported on citrus in South Africa (Moore & Hattingh 2004) and has also been recorded in pome fruit orchards in the Elgin area, along with another mealybug predator *Nephus bineavatus* (Mulsant) (C. Kuiper, pers. comm.). A commercial insectary rears *C. montrouzieri* in South Africa for release as part of a classical biocontrol strategy (Du roi IPM: http://duroibugs.co.za/products/crypto.htm). A number of other natural enemies of mealybugs are reported to occur in South Africa, including *Scymnus binaevatus* (Mulsant) (Coleoptera: Coccinellidae), lacewing larvae *Chrysoperla carnae* (Stephens) (Neuroptera: Chrysopidae), Cecidomyiidae flies and various other ladybird beetles (RealIPM 2013).

The use of nematodes as control agents against mealybugs has shown great potential. Le Vieux & Malan (2013) investigated the potential for vine mealybug (*Planococcus ficus* (Signoret)) control utilising entomopathogenic nematodes (EPNs). The indigenous nematodes *Heterorhabditis zealandica* (Poinar) and *Steinernema yirgalemense* (Tesfamariam, Gozel, Gaugler and Adams) showed 96% and 65% mortality respectively of *P. ficus*. In a study by Stokwe (2009), *H. zealandica* was found to be the most pathogenic nematode species towards *P. viburni*. Stokwe & Malan (2010) found an adult mortality of 78% and juvenile mortality of 76% in *P. viburni* when exposed to *H. zealandica*. The EPNs were also able to infect mealybugs already established within apple cores, preventing any further reproduction of the population (Stokwe & Malan 2010).

The association of ants and mealybugs has been extensively studied, as it is known that the presence of ants tending to mealybugs can disrupt the ability of natural enemies to control mealybugs (Gaigher *et al.* 2011). Samways *et al.* (1982) found that of 123 ant species present in South African citrus orchards, only 11% had associations with mealybugs. The invasive Argentine ant (*Linepithema humile* (Mayr)) has been found to interfere with or prey upon mealybug natural enemies (Williams & Willink 1992) and parasitoids (Daane *et al.* 2007). Interestingly, however, Daane *et al.* (2007) showed that the predator *C. montrouzieri* was more abundant on vines that had mealybugs (*P. viburni*) associated with Argentine ants. Larvae of *C. montrouzieri* were able to mimic the mealybugs and gain acceptance from the ants, allowing the coccinellids to feed upon the mealybugs. In conclusion, the presence of ants associated with mealybugs may cause an increase in mealybug population numbers and thus measures should be taken to control ants in deciduous orchards, especially the invasive *L. humile* (Daane *et al.* 2007).

Other Sporadic pests

The antestia stink bug, *Antestiopsis orbitalis* (Leston), is said to live in natural foliage surrounding orchards year round, moving into the orchards soon after the trees blossom, in order to feed on young fruit (Pringle, unpubl.). This bug is currently controlled as a consequence of the other insecticides that are used in the orchards. No research into the biological control of this species has to date been found. However, it is likely that the use of entomopathogenic fungi (EPF) will effectively control this phytophagous species (J. Kuiper, pers. comm.).

The thrips species *Frankliniella occidentalis* and *F. schultzei* are categorised as sporadic pests. Pringle (2001) recorded that the predatory mite species *Neoseiulus californicus* (McGregor) and *Euseius addoensis* feed on thrips along with phytophagous mites and pollen. *N. californicus* occurs in Western Cape orchards and has been responsible for the reduction in acaricide sprays since its unintentional introduction around 1994/1995 (Pringle 2001; Pringle & Heunis 2006). Thrips are well controlled by *E. addoensis* in citrus (Grout & Stephen 1994) and are likely able to be controlled biologically by the presence of both *N. californicus* and *E. addoensis* in pome fruit orchards. Grout & Richards (1992) and Grout & Stephen (1995) found that two species of trees (*Carpoprotus muirii* and *Eucalyptus torelliana*), often used as wind breaks, provided predatory mite species with a source of pollen which aided in the mites' survival while their prey numbers were low at certain times of the year.

Parasitoids have been investigated for their use as control agents of thrips species, but their effectiveness seems rather poor (Loomans 2006). Gahukar (2004) suggests utilising agricultural practices that encourage the survival of natural parasitoids to aid in the control of thrips alongside predatory mites and naturally occurring ladybird predators.

The use of entomopathogenic fungi (EPF) has been investigated for controlling *F. occidentalis* in field and greenhouse rose plantations. *Beauveria bassiana* (Balsamo) Vuillemin was applied at different concentrations and at various humidities, resulting in population declines of between 50 and 97% (Murphy *et al.* 1998). The potential of utilising EPFs for thrips control is high, although insecticidal EPF sprays need to be earlier than that of insecticides due to the slower control rate of the fungi versus that of insecticides (Murphy *et al.* 1998).

Limited information is available on the biological control of *Bryobia rubrioculus*. It is susceptible to organophosphate insecticides and has thus not been a major problem in pome fruit orchards (Hussey & Huffaker 1976). However, organophosphate insecticide usage is decreasing in Western Cape orchards. According to McMurtry & Croft (1997), no specialised predators of *Bryobia* have yet been found, but it is known that generalist mite predators (such as *N. californicus* and *E. addoensis* already occurring in Western Cape orchards) do feed on this mite species.

Research on the biological control of the other listed sporadic pests *Prasoidea sericea* (Coleoptera: Chrysomelidae), *Eremnus atratus* (Coleoptera: Curculionidae), *Sciobius tottus* (Coleoptera: Curculionidae) and *Lozotaenia (=Tortrix) capensana* (Lepidoptera: Tortricidae) was not found. These pests may not frequently cause damage and have thus not attracted the same attention as have other more economically damaging species. For example, Pringle (unpubl.) records that in eight seasons of monitoring no fruit damage by the leafroller *L. capensana* was recorded on apples in the Elgin area.

Perennial Pests

In perennial pest populations, the GEP is below the ET, but peaks in the population numbers will frequently reach levels above the ET, thus requiring control measures in order to prevent economic loss (Stern *et al.* 1959). (Figure 2.1C)

Obscure mealybug (also known as apple or pear mealybug) (*P. viburni*), woolly apple aphid (*E. lanigerum*) and pernicious scale (*Q. perniciosus*) are the three key perennial pests in pome fruit orchards in the Western Cape of South Africa. European red mite (*Panonychus ulmi*) and two-spotted mite (*Tetranychus urticae*) are perennial in certain parts of the Ceres area.

Obscure mealybug (*Pseudococcus viburni*)

P. viburni is of more concern to growers than the other *Pseudococcus* species. Its biological control options are discussed in the section above, under the heading: ‘Mealybug species’, as the control techniques are all very similar for the different mealybug species.

Woolly apple aphid (*Eriosoma lanigerum*)

Control of *E. lanigerum* is predominantly by the host-specific endoparasitoid *Aphelinus mali* (Haldeman) (Hymenoptera: Aphelinidae). *A. mali* has been effective at controlling *E. lanigerum* above ground, but has no influence on the individuals that attack tree roots (Zhou *et al.* 2013). Temperature significantly affects the parasitism rate of *A. mali* (Chen *et al.* 2006) and it is this climatic variation that may be responsible for the varied success of *A. mali* globally (Mols and Boers 2001). In certain regions, the natural occurrence of *A. mali* has been sufficient to keep *E. lanigerum* below economically damaging levels (DeBach 1964; McLeod 1954; Shaw & Walker 1996), but in other areas, the presence of *A. mali* alone has not been sufficient to prevent economically damaging population levels, particularly in cooler climates (Asante & Dantharayana 1992).

In the Elgin area, *A. mali* is present and is providing a level of control over the woolly apple aphid (WAA) (Pringle, unpubl.). The economic threshold is still sometimes exceeded however, and insecticidal sprays have been conducted in order to suppress population numbers. The combination of predators and parasitoids can effectively control *E. lanigerum* below damaging levels (Gontijo 2011), thus it essential to limit the use of chemical sprays that negatively influence the naturally occurring predator and parasitoid populations for biocontrol to succeed. The most notable groups of predators for control of WAA include the families Coccinellidae, Chrysopidae, Syrphidae and certain predatory Hemiptera (Asante 1997, Short & Bergh 2004).

Nematodes have also been investigated as control agents of the WAA. Berkvens *et al.* (2014) found that *Steinernema carpocapsae* (Weiser) was unable to provide control over *E. lanigerum* in Western Europe. Berkvens *et al.* (2014) attributed this to ‘the inability of the symbiotic bacteria of the EPN to multiply in the haemolymph of the WAA’. They suggest further research to determine whether the same defence mechanism is present in root colonies of *E. lanigerum* and specimens from other parts of the world. On the contrary, Brown *et al.* (1992) found that a broad spray of *S. carpocapsae* reduced WAA numbers on the roots of apple trees in West Virginia, but not significantly. Nematode use for control of edaphic populations of *E. lanigerum* is considered as a promising potential option by Brown *et al.* (1992). Research on indigenous South African nematodes for control of *E. lanigerum* is required.

WAA is susceptible to fungal infection (Asante 1997), and successful control of the pest has been achieved on an apple farm in the Elgin area (J. Kuiper, pers. comm.). *Metarhizium anisopliae* (Metschnikoff) Sorokin has shown great success as a biopesticide that kills the aphid, and simultaneously allows natural predators and parasitoids to survive, which, together, controls population numbers (J. Kuiper, pers. comm.; RealIPM 2013).

Pernicious scale (*Diaspidiotus perniciosus*)

D. perniciosus is mainly controlled by a complex of parasitoids and natural enemies that are complementary in keeping population numbers low (CABI 2014). The parasitoid *Encarsia perniciosi* (Tower) has been investigated for control of *D. perniciosus* (Mani & Baroffio 1997) *and* has shown the greatest success as a biocontrol agent of *D. perniciosus* worldwide, especially in environments in which chemical insecticides are not used (CABI 2014).

Chronic Pests

These species occur in the orchards with a GEP that is constantly above both the ET and the EIL. Control measures are required to reduce the GEP to a new level, the adjusted equilibrium position (AEP) (Pringle 2006)*, that is below the ET* (Stern *et al.* 1959).
(Figure 2.1D)

Codling moth (*C. pomonella*) is of greatest concern. The Mediterranean fruit fly (*Ceratitis capitata*) and Natal fruit fly (*C. rosa*) are also chronic pests in apple and pear orchards. All three species are important quarantine pests.

Codling moth (*Cydia pomonella*)

The codling moth is a key pest in pome fruit orchards and is capable of causing immense damage to apple crops (Barnes 1991), Chemical control is the norm, but according to K. Pringle (pers. comm.) if chemical control of codling moth can be curtailed, then there will be minimal disruption of the biological control of other pests. The use of broad-spectrum insecticides such as azinphos-methyl has resulted in negative environmental effects and has caused secondary pest resurgence, as well as resistance in several different insect pest species (Giliomee & Riedl 1998). The broad-spectrum nature of these insecticides reduces the number of beneficial natural enemies, resulting in reduced natural control of all insect pests (Luck *et al.* 1977). As a result, much research has been conducted on the various alternative control measures for keeping codling moth below economic thresholds.

The release of sterile male codling moths has been initiated in parts of the Western Cape as part of a Sterile Insect Technique (SIT) programme (M. Wohlfarter, pers. comm.). Moths are mass-reared and sterilised using radiation and then released in large numbers into the area of infestation. The sterile males mate with wild females thus resulting in a great reduction in the progeny, reducing the moth's population numbers. There are limitations to this technique, such as the difficulty in separating sexes in the mass-rearing process, but there are many possibilities as well, such as genetic sexing techniques (Franz & Robinson 2011) and F1 sterility (Bloem & Carpenter 2001). The SIT has the potential to be integrated with other control techniques, such as the use of parasitoids, in an Integrated Pest Management (IPM) system.

Parasitoids offer great control of codling moth. Certain species in the family Trichogrammatidae are the only parasitoids that target eggs of Tortricidae (Cross *et al.* 1999b). These egg parasitoids are effective as they attack the egg stage and kill the larvae before they are able to hatch and cause damage (Smith 1996). As codling moth overwinters in the larval stage, it is necessary to release parasitoids annually as they are dependent on host eggs for overwintering, which codling moth does not offer. A release of two species of *Trichogramma* in apple orchards in Germany resulted in a 53-84% reduction in codling moth and *Adoxophyes orana* (Lepidoptera: Tortricidae) damage (Hassan 1992). An indigenous parasitoid *Trichogrammatoidea lutea* (Girault) has been identified in the Elgin area and has been released as part of a supplement to the SIT programme with positive results (Wahner 2008). An added bonus is that *T. lutea* also parasitizes other pest species in apple orchards, including bollworm *Helicoverpa armigera* and apple leaf roller *Lozotaenia capensana*, thus its inoculative release as a supplement to codling moth control would have positive spin-offs for the control of other pests too. Although mass-rearing costs are high (Hassan 1992) and chemical control (when viewed as a single control measure) remains a cheaper and more effective control measure, the greater long-term benefits of utilising parasitoids in an integrated production system should be noted (Wahner 2008). According to Sithanantham *et al.* (2001), the cost:benefit ratio of utilising *Trichogramma* parasitoids was 1:8 and 1:25 in Russia and China respectively, where labour costs are low.

Several other parasitoids have also been investigated for control of codling moth (Cross *et al.* 1999b), but these are mostly larval and pupal parasitoids which are not as effective for commercial systems, due to the damage that is still experienced from the larvae within the fruit, although they may hold value in reducing F_2 population numbers. The use of chemical insecticides for controlling codling moth in pome fruit has resulted in very high standards of fruit being produced, with very low damage levels being standard for the export market. With damage thresholds of as little as 1%, it is difficult for parasitoids to survive among such small host populations (Cross *et al.* 1999). The role of parasitoids is therefore important in an integrated system, but unlikely to provide sufficient control alone.

The SIT is a technique that is most effective at low pest population densities, while parasitoids are known to be most effective at higher pest population densities in which they are able to search out their hosts, but not always at exceedingly high levels. A combination of both parasitoid release and overflooding with sterile insects has been shown to be effective, and better than either of the individual techniques alone (Barclay 1987; Carpenter *et al.* 2004; Cossentine & Jensen 2000). This has been shown theoretically (Barclay 1987) and in practice in several different species (Cancino *et al.* 1996; Wong *et al.* 1992). The use of parasitoids as part of an IPM programme holds great promise and deserves more practical attention for codling moth control in the Western Cape. Integrating alternative food sources, such as flowering plants intercropped in orchards, may be necessary to support parasitoid populations (Landis *et al.* 2000; Sivinski 1996).

Entomopathogenic nematodes (EPNs) are another group of control agents that hold great potential for controlling codling moth. EPNs are able to access codling moth larvae and cocoons in places where insecticides cannot reach, thus offering control over a portion of the population that would normally not be targeted by chemical insecticides. EPNs are able to be mass-reared (Ehlers 2001) and are cost-effective as they do not require formal registration under pesticide regulations at present. The two main families utilised for biocontrol are Steinernematidae and Heterorhabditidae which both harbour endosymbiotic bacteria which are responsible for killing the insect hosts that the EPN species invade (Cross *et al.* 1999a). EPNs are advantageous as control agents in that they are motile and actively seek-out well hidden hosts, have broad host-ranges, high pathogenicity and can tolerate most pesticides (Kovacs 1982).

De Waal *et al.* (2011) investigated the influence of different mulches on the pathogenicity of the indigenous nematode *Heterorhabditis zealandica* (Poinar) against codling moth larvae. Their bioassays showed 88 (±5.05)% mortality of codling moth larvae in pine shavings followed by 72 (±5.05)% in blackwood chips, 67 (±5.05)% in pine chips, 41 (±5.05)% in apple wood chips and 31 (±5.05)% in straw mulch. Two field trials compared straw mulch and apple wood chips, both containing pathogenic nematodes, to investigate the influence on codling moth larvae mortality. The codling moth larvae in the apple wood chip treatment showed a higher percentage mortality in both trials (±62% and ±78%) compared to the larvae in the straw mulch treatment (±34% and ±57%).

In winter, when codling moths are undergoing diapause, no other control methods are able to reduce the population numbers, besides parasitoids that may be able to overwinter with their larval hosts (A. Malan, pers. comm.). Therefore, any reduction of the codling moth population in winter would be a great advantage at the start of the following growing season when the larvae begin to emerge as adults. In an integrated programme, methods such as the SIT, mating disruption and 'attract and kill' are all effective at low population densities, thus if one is able to reduce numbers of codling moth in winter before they emerge again, much damage to crops could be prevented and insecticidal sprays could be reduced. However, as nematodes are sensitive to desiccation (Wright *et al.* 2005) and have specific temperature limitations (Ferreira & Malan 2010), their release in winter in the Western Cape, when temperatures are low, may result in ineffective control. In summer, when temperatures are optimal, the available moisture is low and many codling moth individuals will evade infection when the moth is in adult form. Thus, it is essential to find this balance of optimal temperature and moisture for EPN control of codling moth in the field. Future considerations should include investigating genetic modifications of indigenous nematodes to withstand and perform at lower temperatures, or alternatively investigate the use of exotic EPNs (keeping in line with regulations on importation of exotic species) such as *Steinernema feltiae* (Filipjev) that perform well at much lower temperatures and can withstand desiccation more than other species (Shapiro-Ilan *et al.* 2014).

The use of viruses to control pests may have negative perceptions in the eyes of the general public. However, viruses can be highly target specific. A group of viruses, the baculoviruses, belonging to the family Baculoviridae are specific to arthropods and infect mainly lepidopterans (Cross *et al.* 1999a). This group of viruses is considered safe to use as they do not infect plants or vertebrates (Gröner 1990). Two genera of viruses occur in Baculoviridae: the nucleopolyhedroviruses (NPVs) and granuloviruses (GVs). One of the most widely studied viruses for pest control is the *Cydia pomonella* granulovirus (CpGV).

CpGV has the potential to infect and kill high numbers of codling moth larvae. Ballard *et al.* (2000) showed ≤100% larval mortality in 5 days (after 60 min of exposure) can be achieved in laboratory trials and showed a 98% reduction in fruit damage in field trials. Damage observed was attributed to larvae that fed on the leaves or fruit before they were infected with the virus. This study was important in that it showed that neonate larvae can become infected with the virus when browsing or ‘nibbling’ on branches or foliage before entering fruit, rather than through active fruit feeding. By walking over the virus, larvae became infected. It also demonstrated that longer larval contact with the virus, gave rise to greater probability of death from infection (Ballard *et al.* 2000). The timing of virus application is critical to its effectiveness, as larvae need to be infected at the beginning of first egg hatch before they bore into fruit, where they are shielded from spray applications (Lacey *et al.* 2008).

Lacey *et al.* (2008) speculate how utilising CpGV can contribute to the conservation of natural enemies. Although the virus can infect other tortricids, these other species require a much higher dosage to be killed. Studies showed how CpGV was not infectious to honeybees, whereas the organically certified spinosad was (Arthurs *et al.* 2007).

Resistance to CpGV has been found in isolated cases in Europe (Zichová *et al.* 2013). Resistance to CpGV has been linked to a dominant sex-linked gene (Asser-Kaiser *et al.* 2007). There are however, alternative isolates of CpGV from across the globe to which resistant populations have been found susceptible. It is important to correctly use CpGV in an integrated programme with other non-insecticidal control methods for codling moth, rather than as a stand-alone control technique. In this way, resistance to the virus can be managed and prevented (Lacey *et al.* 2008). On this note, the integration of CpGV with mating disruption, organic pesticides, EPNs, cultural control measures and the release and encouragement of predators will enhance codling moth control, as well as that of certain other pests (Lacey *et al.* 2008).

A biopesticide has been formulated from the bacterium *Bacillus thuringiensis* (*Bt*) which is insecticidal by the formation of crystal proteins during spore formation. These crystal proteins are ingested and toxins form that cause the insect to die due to damage to the insect’s gut (Cross *et al.* 1999a). Different strains of *Bt* are pathogenic to different target groups, which is an advantage allowing for the insecticide to be directed more specifically, rather than killing a wide array of non-target species (Cross *et al.* 1999a, Liu et *al.* 2013). *Bt* degrades quickly in the presence of UV light and heat after application (Pusztai *et al.* 1991) and thus timing of application is important.

Bt use against codling moth generally has not been successful, and this has been attributed to the behaviour of larvae and their tendency to avoid *Bt* uptake before entering the fruit to feed and develop (Andermatt *et al.* 1988). The integration of *Bt* with CpGV was found to be more effective than either technique alone, and their combination had a synergistic effect in controlling codling moth larvae (Liu et al 2013). The combined microbial insecticide (CpGV and *Bt*) is reported to have the potential for low-cost and highly effective control of codling moth (Liu et al 2013). The use of transgenic crops containing the crystal proteins from *Bt* have been developed for pest control, but this is more feasible for large scale cash-crops such as maize, rather than fruits such as apple and pear (Cross *et al.* 1999a). There is also the largely unexplored risk of gene transfer to surrounding natural vegetation.

In conclusion, in order to effectively control codling moth in orchards, it would appear as if a combination of control techniques would provide the most effective suppression of the moth populations in the long term. If the SIT can be managed in such a way that it is feasible for growers to utilise, then its integration with the release of egg parasitoids (such as Trichogrammatidae) will provide an effective backbone for codling moth control. The use of EPNs, preferably in apple wood chips mulch, should be considered for controlling overwintering larvae in order to reduce the number of emerging adults at the start of each season. Supplementation with biopesticides constituted of *Bt* and CpGV during the growing season could effectively replace chemical inputs, allowing for damage levels to be kept low, while adhering to strict residue standards set out by retailers from consumer pressure. While the suggestions laid out here are management intensive, if correctly implemented, the risk of damage from codling moth could be greatly reduced over the long term and a healthier agroecosystem would be maintained.

Mediterranean fruit fly (*Ceratitis capitata*) and Natal fruit fly (*C. rosa*)

A great advancement in biological control of *C. capitata* or Medfly, has been the use of the SIT to control pest populations. In geographically isolated areas, as an area-wide management tool, the use of the SIT can effectively reduce populations to below economically damaging levels. (Barnes 2007; Barnes & Venter 2006). What is required for further success of the SIT in other areas is a steady financial support structure which benefits both investors and the SIT goal at hand, collaboration across all farms, and a well-structured management and monitoring plan (Barnes & Venter 2006; Vreysen *et al.* 2007). The control of *C. rosa* with the SIT is also possible. However, mass-rearing techniques need to be optimised before this is able to be rolled out (Quilici *et al.* 2013).

Parasitoids have attracted much attention for the control of *Ceratitis* species. A review of all parasitoids and predators of tephritid species worldwide is provided by Stibick (2004). Most parasitoids used in biocontrol programmes for Medfly belong to the hymenopteran Braconidae. It has generally been accepted that integrating parasitoid release with the SIT is very effective (Barclay 1987, Rendón *et al.* 2006, Wong *et al.* 1992) and should complement each other as parasitoids are effective at high population numbers, while the SIT is most effective at low pest population density; therefore releasing parasitoids prior to a sterile release programme is complementary (Cladera *et al.* 2006). The release of more than one parasitoid species may also be beneficial, as different parasitoid species may attack different life-stages of the flies (egg, larval instars and pupa) (DeBach & Rosen 1991). A few examples of South African parasitoids of *C. capitata* and *C. rosa* include *Opius humilis* (Silvestri) and *O. africanus* (Szépligeti) (Hymenoptera: Braconidae), *Trichopria capensis* (Kieffer) (Hymenoptera: Diapriidae) and *Biosteres bevisi* (Brues) (Hymenoptera: Braconidae) (Stibick 2004).

The susceptibility of *C. capitata* and *C. rosa* to nematode infection was investigated by Malan & Manrakhan (2009). The nematode species *Heterorhabditis bacteriophora* (Poinar), *H. zealandica* (Poinar) and *Steinernema khoisanae* (Nguyen, Malan & Gozel) were tested against both *C. capitata* and *C. rosa* under laboratory conditions. It was found that the *Heterorhabditis* spp. were more infectious towards both fly species, with an average mortality of about ±62% for *C. capitata* and ±52% for *C. rosa* 24 hours after exposure to the EPNs. The larvae were more susceptible than adults, thus EPN control of fruit flies should focus on the larval stage of the life cycle. *C. capitata* was more susceptible than *C. rosa* to EPN infection in both larval and adult life stages. Research needs to be conducted in the field to determine the effectiveness of EPNs under field conditions.

Utilising entomopathogenic fungi (EPF) for fruit fly control has also recently received interest. Anecdotal evidence for EPF affectivity is present in the field in the Elgin area on certain farms (J. Kuiper, pers. comm.), but scientific studies are required to support this claim. Goble *et al.* (2011) investigated the use of native isolates of *Beauveria bassiana*, *Metarhizium anisopliae* and *M. flavoviride* (Gams & Rozsypal) against both *C. capitata* and *C. rosa* in laboratory trials (as well as false codling moth, *Thaumatotibia leucotreta* (Meyrick), but this is not a pest of pome fruit (EPPO 2013; Venette *et al.* 2003) and is not considered here). The general conclusion from this study was that adult flies are more susceptible to EPF infection than larvae. The greatest mortality, 58%, was experienced by adults of *C. rosa* when exposed to a certain isolate of *B. bassiana*. Mycosis ranged from 1-25% in *C. rosa* puparia and 3-58% in adults. For *C. capitata*, mycosis ranged from 1-10% in puparia and 4-41% in adults. *B. bassiana* was more pathogenic than both *Metarhizium* species, suggesting in this case that use of this fungus has little practical value. However, Ekesi *et al.* (2002) used isolates of *M. anisopliae* and *B. bassiana* from a different source to that of Goble *et al.* (2011) and found very different results. Mycosis in *C. capitata* was visible in puparia with a range of 25-94% and in adults with a range of 36-100%. For *C. rosa*, mycosis was observed in 83-90% of puparia and in 13-100% of adults. Castillo *et al.* (2000) also showed high mortality of *C. capitata* after 10 days of exposure to *M. anisopliae*. Thus, it can be concluded that *C. capitata* and *C. rosa* are both good candidates for control using EPFs such as *M. anisopliae* and *B. bassiana*. The specific isolate of the fungi is critical, as pathogenicity varies from one to another, having a large influence on what levels of mortality can be expected. The use of organic fungal extracts should also be explored as these compounds may hold promise for fruit fly control (Castillo *et al.* 2000).

Ortu *et al.* (2009) reported that female *C. capitata* preferred to oviposit on fruit that was not treated with a bioinsecticide containing *B. bassiana* in both laboratory and field trials and pointed out that the bioinsecticide was as effective as pyrethroids in reducing adult Medfly populations and protecting orange fruit in the field. It would therefore appear as if fungi and fungal extracts hold promise for integration into current IPM programmes and deserve more attention from scientific studies.

Sac spiders (Clubionidae) were investigated as nocturnal predators of Medfly in Israel. Kaspi (2000) found that female sac spiders were attracted to the olfactory cues released by male Medfly. Although it is unlikely that the spiders will play a large role in suppressing Medlfy population numbers, it is interesting to note them as part of the natural enemy complex. The same goes for the invasive wasp, *Vespula germanica* (Fabricius), which although considered a pest species in South Africa, may also contribute to Medfly control in orchards as individuals have been found to seek out and prey upon male Medfly (Hendrichs & Hendrichs 1998).

It is important to note that different life stages are targeted by each biocontrol agent or technique. The SIT focuses on adults; parasitoids primarily target eggs in Medfly (although specific parasitoids are also being used on different larval instars); EPNs and EPFs target larvae in the soil, although EPFs are also very effective in causing mycosis in adults, as long as physical contact is made. In order to create an effective IPM programme against *C. capitata*, the different life stages should all be targeted by utilising a suite of techniques that complement each other. For example, if large population outbreaks are initially controlled by density independent techniques such as ‘soft’ chemicals (e.g. spinosad), or bioinsecticides, techniques such as the SIT can then follow which are highly effective at lower population densities. Combining the SIT with the release of egg-parasitoids will effectively reduce the remaining population to low levels. Assuming environmentally friendly, more specific control techniques are followed, the naturally occurring enemies such as spiders and generalists like coccinellid larvae will also have an influence on remaining individuals. Such suggestions are easily listed in theory, but planning and implementation is extremely technical and needs to be addressed by experienced IPM practitioners.

Concluding Remarks on Control Agents

In order to make management decisions in terms of pest control, one first needs to understand the complex of pest species present in the specific area of concern. Understanding the threat of new pest invasions is also of great importance. This review has outlined the major pests present in the Elgin-Grabouw apple-growing area of the Western Cape in South Africa. Each localised area is likely to vary in terms of pest assemblages and severity of outbreaks. It is thus beneficial to list the non-insecticidal management options for each pest species and allow for growers and consultants to make the final decisions regarding pest control.

From this review, it is apparent that a wide array of biological control options are available and in use in the field. For a functioning biological control system to be in place, it is essential that the use of broad-spectrum insecticides is curtailed. Parasitoids and naturally occurring predators are generally negatively affected by broad-spectrum chemical sprays and it can take time for these naturally occurring, beneficial assemblages to build up again. Providing favourable conditions for the survival of naturally occurring predatory and parasitoid species will always be of benefit to growers.

ENVIRONMENTAL IMPLICATIONS OF RELEASING BIOCONTROL AGENTS

It is critical to address the risks of biological control as it would be naïve to assume that such a pest control measure comes without risks (Samways 1997). Biocontrol is perceived to be a relatively risk-free method encouraged by the public as an environmentally-friendly and more healthy alternative to chemical insecticides (Howarth 1991). However, there has been a lack of sufficient follow up data on biocontrol release programmes, and a lot of information has been gathered as a consequence of researchers being in the field on unrelated studies, at the right place, at the right time (Simberloff & Stiling 1996). Thus, the negative effects of biocontrol releases that have been recorded are likely only a portion of the actual implications on the environment.

Risks are relative to the type of agent being used, the area of application and the amount of research done prior to and during release programmes (Samways 1997). If the life cycle of an agent does not correspond exactly with its host, non-target species may be selected by the agent for the completion of its life cycle (Gould *et al.* 1990). This is relatively unpredictable and may be detrimental to local non-target species (Boettner *et al.* 2000). The indirect impacts of releases need to be given more attention. It is suggested that food webs are used rather than linear food chains in pre-release studies, as food webs are much more representative of the complex ecological interactions in an ecosystem, and may help prevent unforeseen indirect impacts of introducing biocontrol agents (Strong 1997). This applies to predators, parasitoids and pathogens. Certain indirect impacts are difficult to predict, however, for example the entomopathogenic fungus *Beauveria bassiana* has caused lesions in reptiles (Austwick 1980) and deformities in fish (Genther & Middaugh 1992). Quarantine procedures need to be adhered to in order to prevent unexpected pest introductions. This occurred when certain ladybird beetles (Coccinellidae) were released into North America bringing with them parasitoid mites that could potentially have become invasive species themselves (Hurst *et al.* 1997).

The importance of pre-release studies cannot be emphasised enough. Within these studies, not only should the host range of agents be tested, but the habitat range of agents should also be considered. One cannot assume that because an agent was tested for host-specificity in one area that it will act the same way in another area (Howarth 2000). The release of non-indigenous organisms is potentially irreversible and unlike chemicals with known half-lives, biocontrol agents may pose risks to non-target ecosystems and their constituents due to the ability of organisms to reproduce, disperse and evolve (Howarth 1991). This also highlights the importance of post-release monitoring and evaluation, as the successes and failures of programmes can be scientifically studied and the findings made available for the greater scientific community, in order to improve on current techniques. The predictability of the outcomes of release programmes will improve in time, however the release of non-indigenous agents to control indigenous pests (neo-classical biocontrol) should always be approached with caution due to the unpredictable effects of a novel disturbance on an ecosystem and its inhabitants (Howarth 1991).

The dilemma we face is that the specific characters that make biocontrol agents successful are the same characters that allow them to potentially become highly invasive, impacting on non-target species, the environment and human welfare (Howarth 2000). Regulations and legislation must be established and more importantly, enforced to ensure that the risks of releasing aliens into environments for the purpose of biocontrol are monitored and reduced.

Although biocontrol may have environmental risks, we need to weigh up these risks with those associated with other control methods, such as the use of broad scale insecticides. The economic and environmental risks and benefits need to be determined and cross-referenced with other techniques and not treated in isolation; after all, we are aiming for an integrated approach to ensure sustainable crop production into the future.

FUTURE PROSPECTS

Most biological control programmes in orchard settings require the utilisation of complementary techniques in order to keep pests below economic thresholds. The integration of biocontrol with cultural control practices and habitat management to enhance natural enemy populations, along with the SIT, mating disruption and the strategic use of selective insecticides holds the best possible future for sustainable pest-control in orchard systems (Gurr & Kvedaras 2010; Wratten & Gurr 2000).

There is potential for novel techniques, such as the use of Herbivore Induced Plant Volatiles (HIPVs) (Gurr and Kvedaras 2010) or Volatile Organic Compounds (VOCs) (Llusia & Penuelas 2001) in order to artificially assist the attraction of natural enemies to plants with heavy pest infestation. Genetic manipulation of natural enemies in order to make them more efficient or more suitable to the environment is already occurring (e.g. insecticide-resistant predatory mites (Solomon *et al.* 1993)) and holds great promise for further development (Wratten & Gurr 2000).

If the full complex of indigenous natural enemies and parasitoids is investigated in the fynbos biome, the likelihood of discovering indigenous biocontrol agents for use in pome orchards in the Western Cape of South Africa is high. Ecological engineering and pest management on a landscape rather than a farm scale will greatly contribute to the success of an integrated pest management programme with biological control as the backbone of the system.

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3) The environmental value of the Sterile Insect Technique: Where are we now and where are we going?

ABSTRACT

The Sterile Insect Technique (SIT) has received much attention over the last few decades as a targeted approach against certain veterinary and agricultural pests. The SIT is target species-specific and can be integrated with other control options, such as pheromone disruption and biological control, as well as physical and cultural control methods. A meta-analysis was conducted here to assess the efficacy of the SIT, and was used to draw conclusions on the likelihood of the technique being used as a successful biodiversity friendly tool. Results suggest that with detailed planning and efficient management, an SIT programme has a good chance of success. Ongoing SIT programmes worldwide provide examples on the possibilities and limitations for the future of the SIT as well as positive environmental implications. Failed programmes can be attributed to faults in implementation, stakeholders not collaborating and shortages, or inconsistencies in funding, rather than the failure of the technique *per se*. Genetic modifications, particularly of major problem pests, hold great potential for overcoming issues with irradiated insects' lack of competitiveness and quality. The future of the SIT relies on area-wide management of pests and the collaboration of producers, allowing for prevention rather than cure of pest invasions. Overall, the SIT has a positive future as a targeted approach with none of the spillover or insidious effects that many insecticides and certain biocontrol agents may have. Importantly, this leads to an appreciation, along the whole supply chain, that taking such a well-planned approach such as the SIT, not only benefits the local environment but also addresses export drivers such as the increasing demand by consumers to have food that is free of contaminants and is grown in a biodiversity-friendly way.

INTRODUCTION

The Sterile Insect Technique (SIT) is the utilization of a species to control its own species through the mass rearing, sterilization and release *en masse* of that species in an area (Dent 2000). Control is achieved as the sterile individuals mate with wild individuals causing a reduction in fertility and decrease in the population in the following generation. The technique made its debut when Edward Knipling and Raymond Bushland successfully induced sterility in the screwworm, *Cochliomyia hominivorax* (Coquerel) in the 1950s

(Knipling 1959). An area-wide programme was then rolled out, with the screwworm being subsequently eradicated from the USA, Mexico and Central America (Vargas-Terán *et al.* 2005). The use of the SIT has received much attention due to the specificity of the technique and its environmental merits, and is now being used against several insect pest species across the globe (ARC 2013).

The SIT has been successfully implemented on lepidopteran, dipteran and coleopteran pests (Klassen & Curtis 2005). In the Cape Floristic Region (CFR) biodiversity hotspot, for example, the SIT is currently being used on an area-wide basis for management of Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann); codling moth, *Cydia pomonella* (L.) and false codling moth, *Thaumatotibia leucotreta* (Meyrick), especially since risks to the rich biodiversity have to be minimized.

There are four strategic options for the SIT (Hendrichs *et al.* 2005): 1) suppression, 2) eradication, 3) containment, and 4) prevention. The most effective SIT strategy is the prevention of an introduction by the periodic release of sterile insects in an area at high risk of invasion (Hendrichs *et al.* 2005). This has been successfully implemented in Japan against the melon fly *Bactrocera cucurbitae* (Coquillet), as well as in California against the Mediterranean fruit fly (Hendrichs *et al.* 2005).

In order to choose the most applicable research strategy, certain factors must be considered. In terms of the pest, its biology, distribution and ecology all influence which strategy to employ. In turn, the target market for agricultural produce is an important additional factor to consider. Hendrichs *et al.* (2005) list four main types of markets: 1) domestic markets, 2) non-discriminating export markets, 3) low residue export markets, and 4) pest-free export markets. If a producer is looking to export to a pest-free market, eradication would be the best strategy. However, if a producer supplies local markets, suppression may be the best option.

The SIT has great potential as an environmentally-friendly method for controlling more agricultural pests, but has had slow uptake in many areas, where insecticides remain the basis of control. This review aims to highlight the efficacy of the SIT by viewing the overall picture across the globe. By analysing the available and applicable information, the future of the SIT and its application to agricultural systems is assessed, with special emphasis on its role as an environmentally-friendly approach to insect pest suppression and local eradication. The focus here is to conduct a meta-analysis at the global level, and test its applicability and future in the CFR biodiversity hotspot of major conservation importance and where the technique is already in use against agricultural pests on certain woody crops.

METHODS

A search conducted in the Scopus® research database (registered under Elsevier) with the key words ‘sterile insect technique’ OR ‘sterile insect technology’ OR ‘sterile insect release’ AND ‘pest control’ generated a result of 338 papers. The titles and abstracts were used to determine which of these papers are applicable to the aims of this review. The result was narrowed down to 51 applicable papers, as well as book chapters, and further studies from the references of already analyzed papers. The purpose of the meta-analysis was to highlight the history and current status of the SIT worldwide, and to utilize the findings, along with other descriptive data (articles, personal communication and reports) not used in the meta-analysis, to give an overview of the viability of the SIT in the context of fruit production in the CFR.

The meta-analysis aimed to highlight the application of the SIT, and did not focus on the mass-rearing of the control agents or the monitoring practices involved with the technique. The variables considered in each study were: population control, dispersal ability, mating efficiency, influence of climate change, economic cost (short- and long-term), resistance, ecological risk, and risks *vs.* advantages.

META-ANALYSIS AND DISCUSSION

Within the meta-analysis, 35% of the papers discussed control of moth species in the Tortricidae, while 53% discussed the control of tephritid fruit fly pests. The remaining studies either considered hypothetical models, or other families such as Drosophilidae (Alphey 2002; Alphey & Andreasen 2002), in which advances in the SIT have been made. 78% of the studies analyzed were either field-based or reviews, giving some clarity on what is currently happening in practice. 27% of the studies dealt directly with experiments in pome fruit.

As a whole, the meta-analysis revealed very positive results for the application of the SIT as a pest-control strategy. For each variable, the majority of applicable studies gave a positive score, indicating the viability of the SIT as a targeted pest-control strategy. Only one variable, climate change, gave a negative result (Dominiak *et al.* 2000), concluding that the predicted climatic shifts brought about locally in urban areas in Queensland, Australia could potentially increase the range of a pest species (in this case *Bactrocera tryoni* (Froggatt)). An increase in a pest’s range would potentially threaten larger areas of agriculture and would necessitate a larger number of sterile individuals being released over a wider area, increasing the cost and management of an extended SIT programme. Each insect species reacts uniquely to climatic changes, and climatic changes are not uniform across the globe. It is thus essential to conduct physiological experiments on pest species and couple their responses with climatic models to determine how each species will respond to proposed climatic changes, and how this would affect crop production and the use of those species in the SITprogramme.

Pest Control and Environmental Advantages of the Sterile Insect Technique

The SIT is effective against certain pest species by eradicating the target population over time, as long as good planning and management is followed in the programme. However, once a high population of a pest is present, suppression becomes the most favorable strategy, as the demand for a constant supply of sterile insects allows for the privatization of mass-rearing facilities, creating a sustainable system, unlike in an eradication scheme where the demand for sterile insects disappears after eradication occurs (Enkerlin 2005). With a suppression strategy, the pest is then kept below economic injury levels.

The benefits of implementing a SIT programme have been recorded directly and indirectly. Savings arise in the long-term from increased fruit yield (as a result of decreased damage), a reduction in production costs, decreased pesticide costs (with clear, concurrent environmental benefits), increased access to export markets, as well as other indirect benefits such as a reduction in medical costs of labourers from decreased pesticide exposure (Enkerlin 2005). There are other benefits, such as aligning with international biodiversity targets, like the Aichi Targets (CBD 2010), which help to conserve ecological integrity ensuring that food production can continue into the future. The ‘Strategic Goal B’ of the Aichi Targets aims to: “Reduce the direct pressures on biodiversity and promote sustainable use”. Under this goal there is one specific target, target 7, which the SIT would assist in achieving: “By 2020 areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity” (CBD 2010). Sainsbury’s franchise in the UK has developed a set of goals known as the ‘Sainsbury’s 20 by 20 Sustainability Plan’ in which some of the goals relate specifically to sustainable agriculture: “We’ll source all of our key raw materials and commodities sustainably to an independent standard” and “By 2020 our suppliers will also be leaders in meeting or exceeding our social and environmental standards” (Sainsbury’s 2013). It is clear that farming practices will have to adopt technologies that are environmentally-friendly to ensure sustained production, but also to ensure access to international markets as retailers, such as Sainsbury’s, strive towards meeting these goals.

The SIT has been praised as an alternative pest control strategy due to its target specificity. Furthermore, there are few risks with releasing sterile insects into an environment, as long as individuals of a species being released do not become a nuisance, a disease vector, or a species that causes economic damage in its release-form (Lance &

McInnis 2005). The variable *ecological risk* scored extremely well, as only one out of 17 studies mentioned any associated risk (Alphey & Andreasen 2002). This related to the unwillingness of public for genetically modified organisms to be released into the environment, despite the fact that no environmental risks are known or suspected, except from possible range expansion due to climate change. But even this risk is not from the technique *per se*, but rather from a global driver. The virtually non-existent ecological risk and the characteristics of the SIT allow the technique to be integrated effectively with other techniques, such as biological control (which can sometimes have risks (Samways 1997)), mating disruption, physical control and habitat management.

An advantage of the SIT is that it becomes more effective at lower population densities (Vreysen & Robinson 2011). This means that if a constant overflooding ratio is maintained, the sterile:wild male ratio will increase and the affectivity of population suppression will increase (Knipling 1979). It is because of the inverse-density dependent relationship that pre-release methods are almost always used in conjunction with the SIT to bring the initial population size down to a more manageable level. Insecticides are commonly used in pre-release programs, but this goes against the principle of using environmentally-friendly techniques, and threatens natural enemy survival, encouraging secondary pest outbreaks (Nagel & Peveling 2005). This situation needs to be addressed using, for example, alternative pesticides that are less environmentally hazardous. A new insecticide (Spinosad) derived from a compound produced by the bacterium *Saccharopolyspora spinosa* (Mertz & Yao), has been organically certified, and is a suitable alternative to the previously used organophosphate insecticides for pre-release suppression (Nagel & Peveling 2005). Alternative methods such as bait-trapping have also proved to be effective in pre-release suppression (Nagel & Peveling 2005).

A CFR example of SIT success is the Hex River Valley area-wide control programme, established in 1997 against *C. capitata* (Barnes *et al.* 2004; Barnes & Venter 2006; Enkerlin 2005). The valley grows predominantly table grapes and sells to both local and export markets. After three years, insecticide application was reduced greatly, while damage due to *C. capitata* also decreased substantially (Barnes *et al.* 2004). The programme has a benefit:cost ratio of 2.8:1, with a total saving of US$ 150 000 per year (IAEA 2002). The success of the Hex River Valley example has resulted in increased SIT research and implementation in other parts of the CFR.

Limitations of the Sterile Insect Technique

The largest constraint on the SIT relates to the fact that exposing insects to radiation in order to sterilize them causes negative effects regarding the insects' competitiveness. The dispersal ability and mating efficiency fitness of sterile insects is most often lower than that of their wild counterparts due to the mass-rearing, irradiation exposure, handling and transport (Bakri *et al.* 2005; Calkins & Parker 2005). However, pre-release exposure to ginger root- and citrus oils has been shown to increase male *C. capitata* competitiveness considerably (Shelly *et al.* 2007). Methyl eugenol exposure increased sterile male attractiveness to females in *Bactrocera dorsalis* (Hendel) (McInnis 2011). These techniques, among others, such as altering larval diet and development conditions, show promise in overcoming the issue of competitiveness in sterile insects (Hamden *et al.* 2013). All these particular pre-release methods have no known environmental risks.

Lepidopteran species generally require higher irradiation doses to achieve full sterility. However, the offspring (F1 generation) of semi-sterile males have been found to be more sterile than the parents. The F1 generation also becomes male-biased (Bakri *et al.* 2005). F1 sterility is thus a more cost-effective and efficient means of population control that is now being implemented against certain lepidopteran pests (Bloem & Carpenter 2001). Models show that overflooding ratios can be up to one quarter less when using F1 sterility compared to full sterility. As a general theory, two methods of pest control will integrate effectively and complement each other when each control method is effective at a different pest density (Barclay 1987). Aligning with this theory, F1 sterility has been shown to combine very effectively with other control methods such as biological control, mating disruption, host plant resistance, entomopathogenic control, as well as insecticide usage (Bloem & Carpenter 2001). This is because F1 sterility is effective at low pest densities whereas the other techniques are all more effective at higher pest densities.

Current codling moth control programmes, such as the on-going suppression programme in British Columbia, Canada are limited by the release of both sterile male and female moths simultaneously (Vreysen *et al.* 2010). It has been shown (particularly in *C. capitata*) that the release of only males is significantly more effective (McInnis *et al.* 1994; Hendrichs *et al.* 1995). The use of F1 sterility in codling moth could potentially be one way of addressing this issue in the CFR as the F1 generation tends to become male-biased (Bakri *et al.* 2005). Genetic improvements such as the introduction of temperature sensitive lethal (tsl) alleles could also hold potential here (Knipple 2013). The production of males-only in rearing facilities would also allow for increased production of moths, as males are smaller than females, which could allow for higher over-flooding ratios at a reduced cost (Vreysen *et al.* 2010).

The cost of establishing a SIT programme is initially high. Therefore, it is essential that baseline data are collected for an operation to succeed (Vreysen *et al.* 2007). For example, Stotter *et al.* (2014), working in the CFR on the false codling moth (although not a pest in pome fruit (EPPO 2013; Venette *et al.* 2003)), showed that the moth, although indigenous, was almost entirely confined to citrus orchards and certain alien hosts. This means that the SIT can be specifically targeted within crop fields without any distribution of sterile individuals into the surrounding natural area.

There is no return on costs if a SIT initiative fails, which is discouraging for potential investors (Whitten & Mahon 2005). There needs to be collaboration between stakeholders and a committed management team throughout the operation to ensure that releases are timely and monitoring is carried out effectively. Privatization has proved to be important in ensuring the success of many operations (Enkerlin 2005).

Resistance to insecticides has been a major problem for pest control and continues to be a serious issue, as insects are developing resistance faster than insecticides are being developed. The question arises as to whether insects will develop resistance to the SIT. In the meta-analysis, two studies documented a form of behavioral resistance to the SIT. In one instance, wild female melon flies, *Bactrocera cucurbitae* (Coquillett), that had been exposed to mass-released males for some time began to reject matings with sterile males, while females on an island nearby that had not been exposed to sterile males, did not reject matings with sterile males (Koyama *et al.* 2004). The authors interpreted this behavioral change as an inherited form of resistance to SIT. In the second paper, a similar situation occurred with female *C. capitata* in Hawaii (McInnis *et al.* 1996). Interestingly, in both examples, the lab-reared sterile males still mated successfully with females from other geographical areas. It is important to acknowledge these two examples, even though no other reported resistance has been reported. Refreshing mass-rearing colonies periodically with wild-derived colonies can ensure that the quality of insects within a facility does not diminish over time (Whitten & Mahon 2005).

Genetic manipulation of insects, such as temperature sensitive lethal (tsl) alleles for genetic sexing and release of insects carrying a dominant lethal allele (RIDL) is often viewed as high risk in terms of environmental consequences (Alphey *et al.* 2011). However, the use of genetic manipulation to create methods of differentiation between sexes can save expenses in the mass-rearing process (Bloem & Carpenter 2001; Franz & Robinson 2011). RIDL or similar genetic techniques are highly unlikely to result in resistance forming, since they result in the death of individuals acquiring the genotype (Alphey *et al.* 2011). Consistent monitoring would also ensure that resistance is detected and curtailed by utilizing an alternate RIDL strain (Alphey *et al.* 2011).

In September 2014, the only company producing sterile codling moths for release in Western Cape apple orchards was closed down. This was due to the lack of financial support as a result of growers' distrust in the technology and the limited uptake of the technology in the region (M. Wohlfarter, pers. comm.). The question of whether the production of codling moths for sterile releases will start up again in the future can only be answered in time. Will resistance to chemical insecticides or market demands regarding pesticide residue on fruits, force growers to seek viable alternatives in the future? Integration of valuable techniques such as mating disruption with SIT, along with biological control and habitat management may all become serious considerations in the near future.

FUTURE PROSPECTS

Several documented SIT programmes have not succeeded. It is essential to learn from these failed attempts, to ensure that future endeavors do not fail for the same reasons. Vreysen *et al.* (2007) reviewed the situation, with the general conclusion that it is essential for baseline data regarding the area of interest and the pest species to be collected. One cannot take control techniques from one area and directly apply them to another. Each area is unique in terms of distribution, density and dynamics of the target pest population. The topography, ecological and climatic conditions for each area must also be carefully considered. It is also necessary that the baseline data are collected within reasonable time, so that critical changes do not occur in the population between the time the data were collected and the time the control operation starts.

Management considerations are equally as important as the technical components of a SIT programme. All stakeholders involved need to give full support and the public must be aware of the technologies being implemented to ensure their support is granted. Reviews from independent sources are also essential components of the management of a SIT programme (Vreysen *et al.* 2007).

There have been several developments with integrating the SIT with alternate methods of pest control to achieve codling moth population control. Judd & Gardiner (2005) were able to control codling moth populations by utilizing pheromone-based mating disruption coupled with environmentally-friendly tree banding in British Columbia. This methodology eliminated wild moths and overwintering larvae more effectively than the supplementation of the SIT with environmentally-undesirable insecticide spray regimes. This example of a successful, sustainable method of codling moth control should be investigated for use in other parts of the world, in an effort to minimize insecticide residues in fruit and the surrounding natural environments. The integration of the SIT with other forms of pest control will hold the most promise for successfully preventing economic damage in agriculture.

Genetic improvements in the SIT hold great potential for future control. If sterility can be induced through genetic means, it will mean that these insects will be more effective in population control as irradiated insects are known to have reduced competitiveness in the field compared to their wild counterparts. Genetic sexing techniques are essential to optimize the rearing-process and to ensure that male only-releases take place. Significant progress has been made in this regard on *C. capitata* (Hendrichs *et al.* 1995; Franz 2005). There has been research into converting female insects into males by utilizing the conditional expression of a transgene that results in the suppression of a female-specific gene, causing about 95% males and 5% intersex individuals (Pane *et al.* 2002; Saccone *et al.* 2007). This holds considerable potential for several insect species, not only *C. capitata*.

The future relies upon area-wide control through collaboration between affected and potentially affected farmers. By collaborating with import and export areas that have experience with controlling the same pests, optimum control efforts can be maintained across the globe. It is essential to have long term vision and the foresight to plan and ensure preventative measures are taken against serious invasive threats, such as that of *Bactrocera dorsalis* (Hendel) in South Africa at present (Donkin *et al.* 2013). A bottom-up approach is essential for the success of future area-wide SIT programmes, as this ensures that growers are involved from the beginning, giving their willing support, unlike programmes in which farmers are involuntarily involved creating poor operational results (M. Addison, pers. comm.). Importantly, this involves really appreciating that adopting such a well-planned, environmentally-friendly approach not only benefits the local environment, but also addresses export drivers such as the increasing demand by consumers to have food that is free of contaminants, and is grown in a biodiversity-friendly way.

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4) Habitat management in Western Cape pome orchards: optimising agroecological health for improved pest control

ABSTRACT

In order to feed the continuously growing human population, our agricultural systems need to be managed in such a way that allows for increased food production while conserving biodiversity and environmental health. This way, crop production can be sustained into the future for generations to come. At present, the liberal use of chemical fertilisers and pesticides is threatening ecosystem, human and agricultural health. This review looks at habitat management as a method of increasing agroecosystem resilience to arthropod pests, with focus on conservation biological control in pome orchards in the Western Cape of South Africa. Diversification of agricultural systems by introducing flowering plants has been shown to increase natural enemy abundance and can greatly reduce pest pressure on crops. The introduction of floral diversity should be done to replicate natural ecological processes and indigenous species should be favoured in order to maximise biodiversity conservation. Although it is unlikely that habitat management will provide complete control over pests, it is a necessity to strengthen agroecological health and its integration with other environmentally-friendly pest techniques is important in creating sustainable pest management in pome orchards as we head into the future.

INTRODUCTION

The growth of the human population has put increased pressure on farmers worldwide to produce more food. Intensification of farms through increased inputs of chemical fertilisers, mechanisation and chemical pest control have allowed for increased yields. However, the increased productivity and yields are at the expense of the sustainability of such farming practices (Letourneau & Altieri 1999). Due to political and economic forces, farmers are able to reduce their per-unit cost of production by increasing farm size and through specialisation (formation of monocultures), and intensification (Cunningham *et al.* 2013). This tendency has been a major obstacle to implementing alternative, environmentally friendly farming methods that aim to preserve biodiversity (Letourneau & Altieri 1999). However, recent social and consumer pressure has created changes in policy and market demands, which is to the benefit of diversification in agricultural systems. A response to such pressures can be seen in the markets, for example Sainsbury's retail chain in the U.K. has launched a '20 by 20 Sustainability Plan' (available at: http://www.j-sainsbury.co.uk/responsibility/20x20/)

encouraging responsible, environmentally-friendly farming methods. In South Africa, The World Wide Fund for Nature (WWF) and Woolworths have partnered and launched 'Farming for the Future' (King & Thobela 2014) in an effort to encourage sustainable farming practices. As a consumer driven market, these programmes should encourage needed, positive change in our agricultural systems.

Through large scale commercialisation of agriculture, the ecological integrity of agricultural systems has been diminished, and key functions such as food web structure, nutrient cycling, host-plant resistance, as well as biodiversity, have been reduced (Nicholls & Altieri 2004). In response, attention has been given to alternatives, such as agroecology, which focuses on reinforcing the complex ecological processes within an agricultural system to maximise crop productivity, while reducing damage from pests through increased soil health and hence crop health, as well as encouraging biological control though the presence of natural enemies (Altieri 1999).

It is well-known that arthropod resistance to insecticides is an ongoing issue across the world. Alternative measures of pest control are being investigated, such as the use of sterile insects to inundate wild populations of codling moth *Cydia pomonella* and Mediterranean fruit fly *Ceratitis capitata* in Western Cape orchards, or the use of pathogens such as nematodes and entomopathogenic fungi (Barnes & Venter 2006). Biological control forms the basis of pest control in agroecosystems, but its efficacy is threatened by the use of broad scale chemical insecticides (Landis *et al.* 2000), and the lack of resources for natural enemies in terms of food and shelter (Wäckers *et al.* 2005).

For hundreds of years, habitat management techniques have been used by subsistence farmers across the globe. Habitat management aims to utilise techniques that reduce pest densities by limiting their initial colonization, reducing pest reproduction and survival, increasing their natural enemies and increasing the dispersal of pests away from crops when they do establish (Gurr *et al.* 2004). Often techniques aim to diversify the agroecosystem to encourage the activity of natural enemies, a form of conservation biological control. Techniques such as polycropping, intercropping, management of farm borders and management of the soil environment all influence the activity of pests and their natural enemies in agricultural systems. The theory behind habitat management (defined here as management of plant species on and around the farm as well as farm design and layout) techniques in general will be discussed here, followed by a focus on practical examples from pome orchards worldwide, which will help offer suggestions for utilisation of these techniques in Western Cape pome orchards. Habitat management and conservation biological control (CoBC) are a key focus in this review.

ECOLOGICAL FUNCTION OF BIODIVERSITY IN AGRICULTURE

Increasing floral diversity in agricultural systems, in general, has resulted in lower damage to crops and higher numbers of natural enemies (Altieri 1994). A review by Risch *et al.* (1983) of 150 studies showed that plant damaging insects were less abundant in diversified systems in 53% of the cases; in 18%, pest insects were more abundant, 9% had no difference and in 20% of the diversified systems studied, a variable response was recorded. Andow (1991) showed similar results in a review of 209 published studies in which 52% of 287 herbivore species were found to be reduced in polycultures compared to monocultures, while 15.3% of species showed increased numbers in polycultures. By planting certain species in unutilised space around farm borders, or between orchard rows, an array of benefits can be acquired. One of these benefits is the provision of resources for natural enemies, thus encouraging increased biocontrol. Often predaceous arthropods require a supplement of pollen or nectar in their diet for survival and reproduction (Wäckers & van Rijn 2005). This may be in addition to their prey, or a necessity at a certain life-stage.

Conservation biological control (CoBC) has been defined as “modification of the environment or existing practices to protect and enhance specific natural enemies of other organisms to reduce the effect of pests” (Eilenberg *et al.* 2001). CoBC works either to reduce the effect of pesticides on natural enemies (through selective pesticide use, or planned temporal and spatial application) or through habitat manipulation (Gurr *et al.* 2004). The purpose of manipulating the habitat is to provide natural enemies with resources in the form of nectar, pollen, physical refuge sites, alternative prey, alternative hosts and lekking sites (areas in which congregation and mating can occur) (Gurr *et al.* 2004).

There are two hypotheses that relate to why diversification of habitats leads to a decrease in pest damage (Root 1973): 1) the resource concentration hypothesis, and 2) the natural enemy hypothesis. The resource concentration hypothesis suggests that pests will have lower numbers in more diverse systems as the specialist feeders will have difficulty in finding their host plants over confusing chemical stimuli from other plants, physical barriers and/or shading. The pest is likely to spend less time in the habitat. The spatial arrangements of habitats will determine how much influence each of the above-mentioned factors has on the pest’s ability to find its host plant (Risch 1981). The natural enemies hypothesis predicts that a higher density of predators and parasitoids will occur in diversified systems due to the presence of more favourable conditions for their survival and reproduction, such as alternative food sources and shelter (Risch 1981). The feeding habits of the pest are, however, important. Helenius (1998) reported that monophagous insects are influenced more by habitat diversification than are polyphagous insects. Thus, if the dominant pest in a system is known to be polyphagous, diversification may encourage its survival and should be avoided. A detailed knowledge of the ecology of the pests and their associated natural enemies would therefore be a prerequisite in planning what species of plants to introduce into a system with the aim of encouraging CoBC.

There are other benefits associated with a diversified agroecological design that result in a healthier system overall, and which can result in increased plant resilience against pests and diseases. Nutrient cycling in simplified agricultural systems is reduced, and as a result, farmers are reliant on external inputs such as chemical fertilisers to replenish the required balance of nutrients and minerals in the soil (Altieri 1994). Nitrogen-fertilised crops have been shown to be associated with a higher abundance of pestiferous insect species and higher resulting damage compared to crops with organic fertiliser usage (Altieri & Nicholls 2003; Scriber 1984). Mites and aphids in particular are highly susceptible to fertilisation schemes and increased greatly in systems with N-based fertilisation (Luna 1988). Increased N-fertilisation raises the nutrient content in plants, benefitting sap-feeding (sucking) insects such as mites and aphids (Mattson 1980). By integrating nitrogen-fixing plants into a system, the need for external fertiliser inputs can be reduced (Pretty 2008). These plants make nitrogen available more slowly than the addition of external nitrogen sources, reducing the chance of pestiferous species from benefitting. As soil health is integral to the health and resilience of plants, the use of organic fertilisers rather than chemical fertilisers may be advantageous in promoting a wide array of beneficial microorganisms in the soil that can aid in nutrient cycling and forming symbiotic relationships with crop and inter-cropped plants (Nicholls & Altieri 2004). The introduction of intercropped species will also aid in soil conservation and prevent runoff of water as well as providing protection against harsh wind and sunshine (Hargrove 1991; Nicholls & Altieri 2004).

By creating biodiversity in an agroecosystem, complex webs of ecological interactions are established. The additive effect of these interactions on the agricultural system is often more than the singular effect of each component alone (Nicholls & Altieri 2004). By viewing the organisms in a system as part of a food web rather than a linear food chain, complex, often misunderstood interactions, can be defined. By encouraging more complex food webs through diversification, more stable production can be expected with fewer fluctuations of pestiferous species (Southwood & Way 1970). However, not all diversity can be beneficial to crop production. Several examples of unintentional encouragement of hyperparasitoids have been recorded (Stephens *et al.* 1998), as well as the appearance of secondary pests (Bone *et al.* 2009). This stresses the importance of choosing the biodiversity traits that are beneficial to the agricultural system (such as nitrogen fixing and provision of alternate food sources and shelter for natural enemies) (Tilman *et al.* 1996) rather than arbitrarily introducing flowering plant species into the agroecosystem with the aim of diversification.

PRACTICAL EXAMPLES

In China, an apple orchard was planted with two intercrop species, alfalfa *Medicago sativa* (L.) and rape *Brassica campestris* (L.), to assess the influence of these flowering species on the predator-prey ratios in the system (Yan *et al.* 1997). In the first year of the study, the predator-prey ratio was 1:59. This lowered to 1:10 by the fifth year. The economic threshold for mite pests was raised as a consequence of this intercropped system, from 2 to 6 mites per leaf, allowing for a 70% reduction in acaricide use and a 50% reduction in insecticide use for lepidopteran pests (Yan *et al.* 1997). The promising results were improved, however, by replacing *B. campestris* with a weed *Lagopsis supina* (Stephan ex Willdenow). The reason for this was to create a more stable environment by choosing an intercrop species that flowers earlier, allowing for the alternate food source to be available for longer than in the initial experiment of alfalfa and rape in which rape had a late onset of flowering (Yan *et al.* 1997). By making this change, the mite populations were kept below the economic threshold of six mites per leaf, with no required use of acaricides compared to the conventional experimental orchard in which acaricides and insecticides were sprayed several times to control mite and insect pests (Yan *et al.* 1997).

A number of workers have investigated the influence of increased floral diversity on the abundance and diversity of key natural enemies (Altieri 1994; Bostanian *et al.* 2004; Dib *et al.* 2012; Halley & Hogue 1990; Mullinix *et al.* 2010; Song *et al.* 2012; Wyss 1995; Yan *et al.* 1997), but what is needed is more focus on the level of pest damage on the crops in diversified systems (Jonsson *et al.* 2008). This will allow us to truly measure the successes gained for pest control by diversifying systems, as increased abundance and diversity does not necessarily lead to increased pest control (Simon *et al.* 2010).

In the Cape Floristic Region (CFR), Witt and Samways (2004) tested the value of different land management practices for arthropod diversity conservation. They compared a natural fynbos patch to a conventional, insecticide-using apple orchard (= sprayed) and an apple orchard only under fungicidal treatment (= unsprayed). Much higher diversity and abundance of arthropods were found in the fynbos patch compared to the two orchards. However, both orchards showed a similar assemblage of insects, with the unsprayed orchard showing greater species abundance than the sprayed orchard. This study holds great value as it shows the importance of remnant fynbos patches for biodiversity conservation in the agricultural mosaic across the Western Cape within the CFR. These patches also harbour important predators which can contribute to the control of harmful agricultural pests (Gaigher & Samways 2010). Conserving natural remnant patches of fynbos is also beneficial to sensitive endemic pollinators, such as monkey beetles

(Scarabaiedae) (Kehinde & Samways 2011), that are adversely affected by disturbance and whose conservation status could be improved through altering agroecological design. Patches on farm boundaries may form important dispersal corridors and also provide habitats for natural enemies.

The scale of management is an important factor to consider. While a particular grower may adopt environmentally-friendly management techniques, the efforts may be dampened by surrounding land-use practices. For example, Mullinix *et al.* (2010) experimented with an alfalfa (*Medicago sativa*) cover crop in apple orchards in Washington State, USA. They compared the arthropod pest damage between the alfalfa-covered apple orchard and an apple orchard with a grass cover. They found that generalist predators increased in both orchards over the study period and pest damage was greatly reduced by the fourth and final year of study. However, codling moth *Cydia pomonella* numbers significantly increased and were not able to be controlled by mating disruption and naturally occurring enemies. The codling moth damage was above economically acceptable levels, which would be detrimental to a farmer’s ability to market produce. Upon further investigation, it was found that the codling moth pressure was due to mismanagement of surrounding farms and fruit stockpiles, a factor beyond the control of the experimental farm. The moths were subsequently brought under control through integration of mating disruption, orchard sanitation and the use of *Cydia pomonella* Granulovirus (CpGV) (Mullinix *et al.* 2010). On the topic of scale of management, a meta-analysis revealed that farm-scale diversification may benefit biocontrol if the dominant natural enemies are specialists, while cooperative management and landscape management of habitats is required to boost generalist natural enemy populations (Chaplin-Kramer 2011). As a general remark, for the benefit of biodiversity conservation as well as techniques such as the SIT and biocontrol, cooperation between growers across regions is essential to ensure a sustainable agricultural future while meeting conservation targets.

CHOOSING BENEFICIAL PLANT SPECIES

It would be inappropriate to randomly select flowering species to diversify an orchard in the hope of improving pest control. A series of steps should be taken to determine what suite of species would be best suited to the area of interest. Bostanian *et al.* (2004) used the following characteristics when identifying suitable flowering species for intercropping: 1) attractive to hymenopterans and dipterans; 2) seeds easily available and easily propagated; 3) overlapping flowering periods to allow for a constant supply of nectar and pollen and 4) serve as refuges for beneficials that may overwinter. This involved a pre-selection study of observing visitation of arthropods to different flowering species in the area. If a database of flowering plant species and the natural enemies associated with them could be generated for the Western Cape, this would be of great benefit for CoBC and cultural control. It is difficult, however, as in a region such as the CFR, beta-diversity is high and the suite of herbivores associated with natural vegetation may vary considerably from one location to another, making general conclusions of association difficult (Vrdoljak & Samways 2014; Witt & Samways 2004). One must take note of the physical characteristics of both the plants in consideration and the natural enemies that one is hoping to attract. The mouthparts of the arthropods are particularly important to be aware of when choosing flowering species, as in certain plant species, the nectar may be inaccessible to the particular arthropod species present (Vattala *et al.* 2006). The colour of the flowers is another important feature worth taking note of which may influence the flowers' attractiveness to the beneficial arthropods (Kugimiya *et al.* 2010; S. Faure, pers. comm.) In order to maximise biological control of pests, attracting early season predators is important (Yan *et al.* 1997). By doing so, predator populations are more constant and thus pest populations can be stabilized.

Table 4.1: Potentially beneficial plant species for use as intercrops or cover crops in pome orchards. Note that these species are from across the world and may not be suitable for the climatic and ecological conditions in South Africa. This list should be used as a guideline and starting point in finding similar indigenous flowering plants for use in Western Cape orchards. Trials should also be undertaken to ensure that these species do not pose risks as invasive species.

Name	Common Name	Region	Reference
Achillea millefolium	Yarrow	Quebec, Canada	Bostanian *et al.* 2004, Bugg & Waddington 1994
Achillea millefolium	Yarrow	France	Dib *et al.* 2012
Anethum graveolens	Dill	California, USA	Bugg & Waddington 1994
Asclepias syriaca	Milkweed	Canada	Leius 1967
Aster tongolensis	Aster	Quebec, Canada	Bostanian *et al.* 2004, Leius 1967.
Brassica campestris	Rape	China	Yan *et al.* 1997
Brassica juncea	Mustard	Washington, USA	Gonitjo *et al.* 2013
Calendula officinalis	Marigold	Washington, USA	Gontijo *et al.* 2013
Chrysanthemum maximum	Chrysanthemum	Quebec, Canada	Bostanian *et al.* 2004
Chrysanthemum spp.	White daisy	Canada	Leius 1967
Cosmos sulphureus	Cosmos	Washington, USA	Gontijo *et al.* 2013
Daucus carota	Wild carrot	Canada	Leius 1967
Erigeron spp.	Fleabane	Canada	Leius 1967
Eryngium yuccafolium	Rattlesnake-master	Wisconsin, USA	Letourneau & Altieri 1999

Fagopyrum esculentum	Buckwheat	California, USA	Altieri 1994, Spellman *et al.* 2006
Foeniculum vulgare	Fennel	California, USA	Bugg & Waddington 1994
Hordeum vulgare	Barley	California, USA	Pavek & Granatstein 2014
Lagopsis supina		China	Yan *et al.* 1997
Lobularia maritima	Sweet alyssum	Washington, USA	Gontijo *et al.* 2013
Medicago sativa	Alfalfa	Washington, USA	Mullinix *et al.* 2010
Melilotus spp.	Sweetclover	Canada	Leius 1967
Mentha canadensis	Spearmint	China	Song *et al.* 2012
Ocimum basilicum	Basil	China	Song *et al.* 2012
Pastinaca sativa	Wild parsnip	Canada	Leius 1967
Phacelia tanacetifolia	Lacey phacelia	UK, USA	Landis *et al.* 2000, Gilbert 2003
Potentilla reptans	Cinquefoil	France	Dib *et al.* 2012
Prunus persica	Peach	West Virginia, USA	Brown & Schmitt 2001, Spellman *et al.* 2006.
Prunus spp.	Wild plum and cherries	Canada	Leius 1967
Salix spp.	Willow	Canada	Leius 1967
Sinapsis arvensis	White mustard	Canada	Leius 1967
Sisyrinchium spp.	Blue-eyed grasses	Canada	Leius 1967
Solidago spp.	Golden rod	Canada	Leius 1967
Tagetes patula	French marigold	China	Song *et al.* 2012
Tanacetum vulgare	Tansy	Quebec, Canada	Bostanian *et al.* 2004
Taraxicum spp.	Dandelion	Canada	Leius 1967
Torilis arvensis	Hedge-Parsley	France	Dib *et al.* 2012
Trifolium repens	White Clover	France	Dib *et al.* 2012
Trifolium spp.	Clover	Canada	Leius 1967
Triticum aestivum	Wheat	Washington, USA	Fye 1983
Vicia faba	Bell Bean	California, USA	Altieri & Schmidt 1985, Bugg & Waddington 1994
Vicia spp.	Vetches	California, USA	Bugg & Waddington 1994
Viola spp.	Violets	Canada	Leius 1967

LIMITATIONS

On a commercial scale, damage and loss of produce is detrimental to a farmer's business and will hamper the farmer's ability to market produce, especially on an international market where phytosanitary standards have to be met. Bostanian *et al.* (2004) utilised four flowering species (*Tanacetum vulgare, Chrysanthemum maximum, Aster tongolensis* and *Achillea millefolium*) in a Quebec apple orchard and assessed the influence on pest damage over five years, with no insecticidal input. A total of 90.8% of fruit was free of damage in the fifth year. However, leading up to this, unacceptably high levels of damage occurred while the natural enemy complex was building up. This means that growers would experience severe losses for a few years, if a conventional chemically managed farm was converted to a non-insecticidal, habitat management system for pest control. Integration with other environmentally-friendly techniques, and a slow conversion (possibly by gradually increasing set aside areas with less extensive insecticide applications) would have to take place for habitat diversification to be economically viable.

It is unlikely that habitat modification and cultural control can be used as stand-alone methods of pest control. The need for inputs such as selective pesticides or the discretional spatial use of insecticides (for example, spraying alternate rows) may be necessary at times of pest outbreaks. By enhancing the ability of natural enemies and parasitoids, the need for regular, timed pesticide applications may be reduced though, allowing for resistance to these chemicals to be curtailed.

As cultural control and CoBC are techniques, no particular product is produced that can be exploited to produce a source of income for researchers and investors (Dent 2000). This may be to the detriment of the techniques as pest control measures, compared to techniques such as insecticide-usage, whereby large amounts of capital return are possible due to the production of unique, marketable products. Research efforts are thus largely funded by universities and government institutions themselves, and less interest is gained from important role-playing organisations in industry. An interesting approach has been taken in California which may allow for capital return in the field of environmental management for pest control. Commercially available seed mixes of beneficial flowering intercropping plant species are sold. These seed mixes are available for different crops and are intended to be sown at different times of the year for maximum benefit (Bugg & Waddington 1994). Caution should be taken though, as increasing plant diversity does not always guarantee increased pest control.

Any species introduced into an agricultural system must also not compete with the production crop for resources. Careful attention should therefore be given to the design of systems to ensure that the growth of introduced species does not influence the quality or growth of the fruit. In a region such as the Western Cape of South Africa, water-wise indigenous species should be prioritised as candidates for diversifying orchards due to the limited availability of water in the area.

FUTURE PROSPECTS

A management technique known as the push-pull technique has shown great potential for controlling pests in agriculture. This method employs the use of ‘push’ components that repel pests away from the target crop, as well as ‘pull’ components that lure the pests towards a trap crop or area in which their populations can be destroyed (Cook *et al.* 2007). Beneficial arthropods such as parasitoids and other natural enemies can also be manipulated by these techniques. Both visual and chemical stimuli are utilised to manipulate the pest or beneficial arthropod. Semiochemicals (chemicals or pheromones that evoke a response in another organism) have the widest opportunity for use as push and/or pull components and can be synthetically produced or even produced in plants that naturally produce volatile compounds or that have been programmed to do so through genetic manipulation (Agelopoulos *et al.* 1999; Aldrich *et al.* 2003; Pickett *et al.* 1997). Visual stimuli most commonly occur in the form of habitat diversification through intercropping or the use of border and trap-crops. These crops will act to disguise the production crop visually and chemically through confusing stimuli (push) or they will act to lure pests away (pull) due to increased attractiveness compared to the production crop. The use of intercrops and border crops can be enhanced by utilising semiochemicals and other repellents and attractants (Cook *et al.* 2007).

The purpose of the push-pull technique is to minimise environmental harm, while providing effective and efficient pest control strategies in a sustainable manner (Cook *et al.* 2007). The use of push and pull components individually have and are being utilised in agriculture today. However, the combined influence of creating deterrence from the production crop and attraction towards a more appealing stimulus is proving to be much more effective (Cook *et al.* 2007) and can even negate the use of insecticides altogether (Khan *et al.* 2011). As pests will be congregated in one area, it is possible to control the entire population with a much smaller quantity of pesticide, or ideally through biological means.

The greatest success has been seen in small scale agriculture in Kenya. In maize fields, the legume *Desmodium uncinatum* (Jacq.) is planted as an intercrop to repel the major stemborer pests and to reduce *Striga* weed pressure. Napier grass *Pennisetum purpureum* (Schumach) is planted as a border crop to act as a pull component to which the stemborers are attracted. The *Desmodium* intercrop not only acts as a push component but also acts as fodder for livestock, increases soil fertility and suppresses the *Striga* weed species though several mechanisms (Khan *et al.* 2008). This has allowed for very effective pest control, increased yields and income and has greatly reduced and often eliminated the use of insecticides in these areas (Khan *et al.* 2011).

The push-pull technique has great potential to be successful in perennial systems such as pome orchards. The permanence of the orchard system provides the ideal opportunity for a combination of strategic diversification and border or trap crops to be established that encourage beneficial arthropod populations providing biological control, and utilisation of the push-pull technique. Certain focussed research has been conducted on individual push and pull components for certain pome-pests (see: Prokopy 1968 & Prokopy *et al.* 2000), but to our knowledge no functioning holistic farm scale push-pull strategies have been used in pome orchards anywhere in the world. This should be an area of high level focus for sustainable pest control and production into the future.

Mulches have been tested for their effect on arthropod diversity in different crops. The horticultural benefit of increased organic matter in soils is fairly well known, having a positive influence on soil humidity, temperature and soil structure (Cook *et al.* 2006), as well as increased microbial activity which has been found to improve pest resistance in crops (Altieri & Nicholls 2003). In the Western Cape of South Africa, Addison *et al.* (2013) tested the influence of mulch layers on arthropod diversity. They found higher arthropod diversity and lower pest diversity in mulched plots compared to non-mulched controls. This is consistent with research from Australia where Thomson & Hoffman (2007) also found increased diversity of arthropods in mulched vineyards, including predatory dipterans and hymenopterans in the vineyard canopy. In apple orchards in West Virginia, USA, herbivorous species including woolly apple aphid, *Eriosoma lanigerum*, were reduced in plots in which organic mulch was applied (Brown & Tworkoski 2004). In an effort to create more holistic, sustainable agricultural systems, the use of mulch covers to improve orchard health and pest management should be investigated further in Western Cape apple orchards.

Reflective mulches have successfully been used to repel aphids and reduce aphid-borne viral infection in vegetable crops (Brown *et al.* 1993; Stapleton & Summers 2002; Summers *et al.* 1995). Increased yields were experienced when using these UV-reflective mulches too (Brown *et al*. 1993). The incoming aphids are repelled by silver pigments or reflective surfaces included in the mulch, decreasing the pest's incidence in the crop. Research in apples has shown an increase in fruit colour when using these reflective mulches (Mika *et al.* 2007), but in this regard there are limited studies focussing on pest control in orchards. This could also hold potential for future research.

SUMMARY

A truly sustainable future can be found in agriculture through a paradigm shift to more ecologically-based farming principles that involve relying on the resilience and suite of functional processes associated with biologically diverse systems. This change will have to be adopted slowly, however, and it is unlikely that we will see major shifts in agricultural design on a commercial scale, due to the risk of complicating management and the general scepticism of farmers to implement changes (Nicholls & Altieri 2004).

Cultural control and habitat management are not necessarily capable of providing a level of control that would inhibit economic damage, but they are important components in developing a ‘coherent, holistic approach’ (Dent 2000) that justify more research and practical interest. As has been mentioned already, widespread resistance of arthropods to chemical pesticides and the widespread damage to our natural environments are threatening our biodiversity and our potential to sustain healthy crops into the future. Our focus should concentrate on redesigning agricultural systems to maximise inherent strength against pests through integrated pest management and increased soil and plant health, while embracing techniques such as chemical control as a back-up to be used at times of severe stress (Nicholls & Altieri 2004). Habitat diversification and maintaining remnant patches of natural vegetation are important components in this shift. It is important to choose the functional traits associated with diverse systems and manage these appropriately, rather than introducing floral species to an orchard just for the sake of increasing diversity. Research interest should focus on indigenous, water-wise plants that would fill these functional roles in agroecosystems in the Western Cape, in order for naturally occurring enemies to be favoured, and to avoid any risk of invasion by these plants into the system.

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5) Pheromones and physical controls for economically important arthropods in Western Cape apple orchards

ABSTRACT

Widespread resistance to chemical insecticides encourages exploration of novel pest control technologies. In the Western Cape of South Africa, codling moth *Cydia pomonella*, Mediterranean fruit fly *Ceratitis capitata* and banded fruit weevil *Phlyctinus callosus* are three pests of economic importance. By utilising techniques that do not rely on intense chemical insecticide usage to control these and other pests, the natural enemy complex can be enhanced in apple orchards, allowing for biological control to play a more important role in controlling pest populations. The use of pheromones in mating disruption has been shown to have great effectiveness over codling moth and continues to be used as a widespread integrated control approach. 'Attract and kill' methods have been less successful for codling moth but are widely used for Mediterranean fruit fly. Other novel techniques discussed here include physical barriers such as sticky bands and trenches which provide effective banded fruit weevil *Phlyctinus callosus* control. Host-plant resistance as well as the merits and possible negative consequences of its integration into orchards are discussed. A brief discussion of an emerging control technique, substrate-borne vibrations, reveals a possible future control technique, although this is unlikely to be utilised in Western Cape apple orchards in the near-future.

INTRODUCTION

In Western Cape apple orchards, the most economically important pest is codling moth, *Cydia pomonella* (L.). While its control has been dominated by insecticide spray programmes in the past, including environmentally damaging organophosphate applications (Riedl *et al*. 1998), resistance to these chemicals is a major on-going issue and alternative control techniques are essential to ensure continued suppression of this pest. Concerns over human-health and increasing restrictions on insecticide usage, particularly by certain overseas importers, also create demand for alternative pest control techniques. Another pest of great economic importance is the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann). Females lay eggs under the surface of fruit and larvae bore into the fruit, rendering them unmarketable (Thomson *et al.* 2001). Any control measures that will keep these species, and others, below economically damaging levels without disrupting the natural enemy complexes in orchards are the focus in this review.

Semiochemicals can be defined as chemicals that assist in interactions between organisms (Nordlund 1981). They can be differentiated into pheromones and allelochemicals. Pheromones act to convey messages between members of the same species (intraspecific activity), while allelochemicals convey messages or signals across different species (interspecific activity) (Karlson & Butenandt 1959). Semiochemicals allow Integrated Pest Management (IPM) practitioners to control pests in a species-specific, non-disruptive manner. Careful planning can allow for very effective use of pheromones for monitoring purposes, as well as for mating disruption (MD) and attract-and-kill methods of pest control in orchards. Certain pheromones and allelochemicals are being investigated and applied for use as components of the 'push-pull' technique. The technique employs the use of 'push' components that repel pests away from the target crop, as well as 'pull' components that lure the pests towards a trap crop or area in which their populations can be destroyed (Cook *et al.* 2007). This is a promising technique that incorporates integrated factors that work together in creating a holistic pest management framework (see: Khan *et al.* 2011).

Other non-disruptive techniques which will be discussed here include the use of physical barriers such as sticky bands applied to tree-trunks, trenches aimed at limiting curculionid beetle movement and the integration of host-plant resistance into orchards. Any other novel techniques are also considered.

CONTROL MEASURES

Mating Disruption (MD)

Codling moth females release volatile pheromones that attract males to them in order for mating to occur (Bartell 1982). By releasing chemically-identical synthetic pheromones into the orchard environment, the male codling moth follows false plumes and mating with females is minimised, or does not occur. MD is adopted by almost all apple growers in the ElginGrabouw region of the Western Cape, forming the backbone of codling moth control in the region (M. Wohlfarter, pers. comm.). It is important to note that when MD is utilised, pheromone trapping systems used for monitoring populations become much less reliable (Brunner *et* al. 2002; Pringle *et al*. 2003). Decisions regarding control measures should rather be based on physical damage assessments, supplemented by pheromone-trapping, in orchards where MD is utilised (Pringle *et al*. 2003).

Pringle *et al.* (2003) conducted a study over several growing seasons assessing the influence of MD on codling moth numbers, as well as percentage fruit damage. They found a substantial decrease in fruit damage, from 30-40% prior to MD, down to 1.2% fruit damage in the first season of application. This damage level of 1.2% was never surpassed in the six-year study, with fruit damage remaining low throughout the study period. Moth population numbers reduced from 1.10 to 0.17 moths/trap/week on one farm (Geelbos) and from 6.23 to 0.12 moths/trap/week on another farm (Grogans) under MD. A further positive outcome was that insecticidal sprays were halved after introducing MD as a control technique, while the moth population still remained low. Insect growth regulators (IGRs) were also used in this study, which assisted in codling moth control and acted as a means of resistance management, prolonging the life of other useful insecticides. Pringle *et al.* (2003) showed how an integrated approach (utilising insecticides, MD and IGRs) can effectively control codling moth and keep populations below damaging levels in Western Cape apple orchards. A study by Bloemfield (2003), also in the Elgin area, produced similar results and showed that utilising MD was highly successful at reducing codling moth populations and reducing fruit damage to levels that were undetectable in most orchards. Insecticidal sprays were also reduced and the importance of utilising MD as a resistance management tool is highlighted.

In Washington State in the western USA, an area-wide MD programme was established in 1994 (Brunner *et al*. 2002; Calkins & Faust 2003). This programme named CAMP (Codling Moth Areawide Management Project) had five separate focus areas totalling 1064 ha. These areas experienced great reductions in insecticide applications (down to an average of 0.5 applications per season), as well as a great reduction in fruit damage levels at harvest (down to an average of 0.02% damage). What is interesting to note in the CAMP orchards, is that no outbreaks of secondary pests occurred during MD management, which the authors attribute to a reduction in broad-spectrum insecticide applications. Natural enemy numbers were found to be higher in CAMP orchards, while secondary pest numbers were lower. Damage from true bugs (Pentatomidae and Miridae) was however, slightly higher in CAMP orchards, and spider mite populations also increased (Brunner *et al*. 2002). Widespread adoption of MD has occurred in Washington in an effort to control codling moth populationsand the area under MD increased to 54 000ha by the year 2000 (Calkins & Faust 2003).

There are, however, limitations to the technique that must be considered. Damage in orchards seems to be higher on orchard boundaries, thus insecticide application may be necessary to control populations in these areas (Bloemfield 2003; Calkins & Faust 2003). External sources encouraging moth numbers to increase pose a threat of migration into the orchard environment, also increasing the vulnerability of orchard boundary rows. External sources may include surrounding mismanaged orchards, fruit bins or stock piles (Pringle *et* *al.* 2003) in which moth populations can flourish. MD is heavily influenced by weather conditions, such as wind and temperature (Bloemfield 2003; Cardé & Minks 1995). Wind can easily cause great dispersal of the pheromone plumes, while low temperatures result in less pheromone being released from the dispensers (Suckling *et al*. 1999). Slopes and open areas are also limiting factors in MD orchards (Cardé & Minks 1995). Pheromones tend to sink in air, which means that if dispensers are placed down a slope, individuals upslope will not be influenced by the pheromone plumes (Riedl *et al.* 1998). Open spaces cause internal borders to form, which would increase the likelihood of damage from moths. In addition, population density is a major factor influencing the effectiveness of MD (Pringle *et al*. 2003; Calkins & Faust 2003).

Resistance to MD in tea by the smaller tea tortrix *Adoxophyes honmai* (Yasuda) (Lepidoptera: Tortricidae), which belongs to the same family as codling moth, was shown in Japan (Mochizuki *et al.* 2002). Over time, less disruption occurred in a population that was continuously exposed to a certain pheromone compound. When the same compound was used in MD dispensers on populations not previously exposed to it, very high levels of disruption occurred. Upon mixing the pheromone disruptants and exposing the original population to these new blends, very high disruption was observed again (Mochizuki *et al.* 2002). These results suggest the ability of moths to gain resistance to MD, yet at a rate much slower than to insecticide treatments. Nonetheless, resistance management techniques may also be necessary in MD application against codling moth in Western Cape orchards, especially if disruption figures begin to decline.

Codling moth can have as many as four generations per season (Riedl *et al.* 1998) in the Western Cape, with populations often reaching high levels. Enough dispensers need to be present to ensure that female moth's plumes are adequately masked by the synthetic pheromones. This can become financially costly, but in some areas (in the USA) where codling moth MD has been successful, fewer dispensers per hectare are now being utilised with effective population control (Brunner *et al*. 2002). Because MD is effective at low to medium population sizes, other control techniques (such as the SIT, inundative biological control, entomopathogens and soft or more species-specific insecticides) need to be integrated with MD for it to be effective.

Brunner *et al.* (2002) emphasize that MD will continue to be promoted because of its long-term benefits for biological control of pests due to its species-specificity. The ongoing pressure to reduce use of broad-spectrum insecticides and concerns over human and environmental health, will also work in the favour of MD uptake. Factors that may limit MD uptake include the relatively high cost of MD and farmers' apprehension of utilising MD due to a perceived risk of crop damage when not utilising conventional spray programmes (Brunner *et al*. 2002).

Substrate-Borne Vibrations

Arthropods communicate in many ways, including the use of chemical signals (see mating disruption above), visual signals and audio signals, but also through mechanical vibrations (Polajnar *et al.* 2014). By understanding the complex inter- and intraspecific communication between arthropod individuals, it is possible to interfere in a specific sensory manner and develop novel methods of pest control. Acoustic methods have been developed for monitoring insect populations (Walker 1996) and are being investigated for use in pest deterrence (Hofstetter *et al*. 2014). The use of mechanical signals in arthropod communication and the ways in which this can be manipulated for the benefit of pest control are reviewed by Polajnar *et al*. (2014). As of yet, no research has been conducted on the use of mechanical vibrations as an interference technique for any of the apple pests found in the Western Cape, although similar pests have been studied elsewhere (see Poljanar *et al*. 2014).

‘Attract and Kill’

‘Attract and kill’ (also ‘lure and kill’) methods of pest control work by utilising an attractant to lure pests to a central area, device or bait where they will be killed by contact or ingestion of an insecticide, or by other means such as an entomopathogenic fungus (Dent 2000). Oriental fruit fly, *Bactrocera dorsalis* (Hendel), has successfully been controlled on Rota Island in the Marianas through utilising a bait of methyl eugenol combined with an insecticide (Steiner *et al.* 1965). Besides this flagship control example, several other successful cases of effective fruit fly control have occurred using ‘attract and kill’ worldwide (Broughton *et al*. 1998; Koyama *et al*. 1984). Methyl eugenol is a natural constituent of many fruits and plants and is highly attractive to fruit flies (EPA 2006; Tan & Nishida 1996). Mediterranean fruit fly *Ceratitis capitata* has been controlled using attractants such as methyl eugenol or protein hydrolysates (Vargas *et al*. 2002) combined with an insecticide. However, resistance to these insecticides (Magaña *et al.* 2007) would render the specific ‘attract and kill’ method ineffective. More environmentally friendly alternatives to these chemical insecticides that are still effective in killing the fruit flies are being investigated (Peck & McQuate 2000). An example of an alternative, more environmentally friendly insecticide being used is Spinosad, which is derived from a bacterium *Saccharopolyspora spinosa* (Mertz and Yao), and has been shown to be less harmful to mammals and the environment than other conventional insecticides (DowElanco 1994).

Poison bait sprays are widely used for fruit flies across the world (K. Pringle, pers. comm.). However, little research has actually covered the behavioural response of *C. capitata* to the bait spray droplets (Prokopy *et al.* 1992). The more selective nature and more targeted approach of utilising ‘attract and kill’ makes this technique one worth pursuing as part of an integrated fruit fly control programme into the future.

Charmillot *et al*. (2000) describe an ‘attract and kill’ system that is being utilised in South Africa. A paste is made that contains an attractive sex-pheromone mixed with an insecticide (permethrin). The paste is applied to trees as small droplets and causes males to be attracted to these droplets. Males come into contact with the droplets and are killed by the insecticide. Charmillot *et al*. (2000) conducted a study in Switzerland on the effectiveness of the technique and reported that codling moth populations were kept at very low numbers, sometimes disappearing from certain orchards. Because the insects are killed, in theory this technique should work better than mating disruption, which confuses male insects, but allows them to continue searching for mates. In practice though, the ‘attract and kill’ has not worked well for codling moth in the Western Cape and is currently not being widely utilised (K. Pringle, pers. comm.).

Due to the pathogenicity of entomopathogenic fungi and nematodes to both codling moth and fruit flies (Cross *et al*. 1999; Goble *et al*. 2011; Malan & Manrakhan 2009), arguably research should be conducted into utilising these pathogens as killing agents rather than the current techniques of utilising predominantly harmful chemical insecticides in ‘attract and kill’ application. This would not only make the ‘attract and kill’ technique more environmentally-friendly, but would also be a means of preventing further resistance to the often useful chemical insecticides.

Sticky Bands/ Trunk Barriers

The use of physical barriers to control pests is an age-old tradition. Pryke & Samways (2007) conducted a study on the use of a commercially available exclusion Sticky polybutene barrier called Plantex® along with trunk barriers made from corrugated cardboard. The cardboard acts as a refuge for banded fruit weevil *Phlyctinus callosus* (Schönherr) (Barnes 1982) and is fastened around the trunk of the trees with wire, while the Plantex® bands act as sticky barriers which the beetles cannot cross. Pryke & Samways (2007) found no beetles on the heads of vines whose trunks had Plantex® barriers applied, compared to weevil presence in vine heads without the barriers. Vine bunches were also assessed, with high weevilnumbers found on unprotected vines, compared to only a few individual beetles found on bunches with Plantex® barriers. Clearly, the use of these barriers is effective in excluding banded fruit weevil from reaching valuable fruit in tree canopies (note that banded fruit weevils are unable to fly (Annecke & Moran 1982), thus rely on walking up the stems to reach the canopy). Uptake of sticky bands/trunk barriers in commercial systems may be slow due to the labour intensiveness and time required to position these barriers on the trunks of trees within the orchard. Strong winds in the Western Cape raise a lot of dust which build up on the sticky bands over time, rendering them less effective later in the season, which is a limiting factor to be considered.

Ants are known to form associations with mealybugs due to the honeydew reward that they receive, which may interfere with the biocontrol of these pests (Buckley 1987; Gaigher *et al.* 2011; Way 1963). James *et al*. (1998) showed in citrus orchards, that by using plastic exclusion barriers impregnated with an insecticide, an average of 92% of ants could be excluded from the tree canopy over four growing seasons. Vanek & Potter (2010) utilised sticky exclusion barriers on trunks of sugar maple trees to inhibit ants tending to two scale insect species, *Eulecanium cerasorum* (Cockerell) and *Neolecanium cornuparvum* (Thro). They found 92-100% less ants in trees with the sticky bands, and increased natural enemy activity, resulting in a reduction of between 54-69% in the scale population. Excellent control of ants has also been achieved on South African guavas and citrus using sticky banding (Samways *et al.* 1981; Samways & Tate 1984), with an economically viable and effective band being widely deployed (Samways & Tate 1985). By using a similar technique in Western Cape apple orchards, mealybug infestations could be reduced by excluding ants and following practices that allow for natural enemy populations to thrive. It is important that orchards are well-maintained though, as any branches or other objects drooping to the ground can act as bridges for ants and possibly banded fruit weevil, allowing them to reach tree canopies, evading the trunk barriers. In a similar regard, orchard sanitation is an important management factor that is necessary to reduce pest infestation. Removing dropped fruit from the orchard floor may reduce populations of insect pests and can reduce the spread of disease.

Trenches

The Colorado potato beetle *Leptinotarsa decemlineata* (Say) is a worldwide, major economic pest of potatoes (Radcliffe *et al.* 1991) which has developed resistance to almost all chemical compounds (Alyokhin *et al*. 2008), thus alternative management tactics have been investigated. The use of plastic-lined trenches is one such alternative that has produced good control over the populations. Trenches lined with plastic were placed alongside a potato field between the crop and the overwintering area in Canada (Boiteau *et al*. 1994). As the beetles migrated to or from the overwintering site, they would fall into these trenches and remain stuck inside, unable to crawl out. This greatly reduced the number of beetles reaching the crop and also reduced the overwintering population by stopping beetles from reaching the overwintering sites after leaving the crop. Boiteau *et al.* (1994) showed that on average, 84.3% of beetles that fall into the trenches are retained. Laboratory trials showed that clean plastic does not inhibit the ability of beetles to walk on vertical walls. However, fine dust particles accumulating on the tarsal pads of the beetles inhibited contact between the tarsi and the plastic walls, significantly reducing the beetles' ability to climb out. Thus, it was concluded that in field situations, the trenches must be at a minimum angle of 65° to inhibit beetles climbing out. Rainfall can assist in cleaning the dust off the plastic walls and off the tarsi, and helps the beetles escape, but dust quickly accumulates again as the trenches dry-up (Boiteau *et al*. 1994). A total of 40-90% of the summer adults of *L. desemlineata* was removed from the crop by using trenches. A local pest, the banded fruit weevil *Phlyctinus callosus*, shows a similar phenology to the Colorado potato beetle in that adult weevils walk up trees to feed in the lower regions and the canopy and oviposit in the soil in which larvae develop, pupate and eventually emerge as adults again (Barnes 1989). Apple orchards could be isolated by using trenches in the Western Cape to protect the trees from external sources of infestation once a population has been managed from within. High winds in the

Western Cape may pose a problem, either filling up the trenches with soil and debris, or by blowing weevils across trenches. Albeit labour intensive, this method is an environmentally friendly, low-cost option that could possibly assist in the control and monitoring of banded fruit weevil in the Western Cape.

Shade-netting

Shade-netting over apple orchards could provide protection from wind, hail, sunburn and some insect pests. Although netting may provide some benefits to pest management, this would require a major shift in orchard management techniques and will not be discussed here.

Host-plant resistance

Host-plant resistance (HPR) is an effective method of decreasing damage from arthropod pests. Plants can be bred for desirable traits, or genes can be inserted into the plant genome. Two main groupings of genes can be used in HPR: those that are plant-based and those that are non-plant based, such as toxins of bacterial origin (Dent 2000). Once a resistant variety is established, HPR is advantageous in that it is pest-specific with no detrimental effect on natural enemies, it lasts for a long period of time, is cost-effective and is compatible with other pest control techniques (Maxwell 1985). However, there is the chance of resistance forming towards HPR techniques (Giliomee *et al*. 1968) due to the very fact that orchard trees remain in place for many years, allowing for arthropods to develop resistance mechanisms. It is possible to genetically modify insecticidal properties into crops, such as the use of *Bacillus thuringiensis* (Bt) toxins in vegetable crops (Altieri *et al*. 2004). However, this form of HPR may cause distrust in consumers and may also have negative consequences on the surrounding environment, non-target organisms (such as pollinators) and natural enemies (Altieri *et al*. 2004). Having said that, the costs and benefits must be weighed up in order to make informed decisions, since around 22.3 million kg less formulated pesticide products have been used due to utilising genetically engineered soybean, corn, canola and cotton (Phipps & Park 2002). Integrating HPR with manipulation of the agricultural environment (such as habitat diversification) could encourage natural enemy activity and reduce reliance on chemical insecticides. Research into woolly apple aphid *Eriosoma lanigerum* (Haussmann)-resistant strains of apple tree is occurring in South Africa at present (HortGro 2013). Stöckli (2009) made interesting progress into HPR for several important pests of apple in Switzerland, including codling moth. Research into HPR should continue in apples as integration with other techniques could result in a viable means of reducing pest-pressure in Western Cape apple orchards.

CONCLUSIONS

Mating disruption is a very useful resistance management technique and has shown its effectiveness in reducing pest pressure, especially in codling moth. It is limited by its effectiveness only at low to medium population levels and the undulating topography of Elgin Orchards. MD should be adopted by all growers, and integrated with other techniques, as it is not effective as a stand-alone method (Riedl *et al*. 1998).

‘Attract and kill’ theoretically should be more effective than MD. However, in the field, its effectiveness has been limited, particularly for codling moth (K. Pringle, pers. comm.). Bait sprays, pastes and traps have been used for Mediterranean fruit fly control and continue to be useful tools in integrated pest management. However, the labour required to apply pastes and the increasing resistance to insecticides are limiting factors associated with this technique. Entomopathogens could effectively replace the insecticidal component in ‘attract and kill’ systems.

Physical barriers such as sticky bands are effective control measures for specific pests. However, on a commercial scale, protecting every tree with a physical barrier around the tree-trunk is a laborious and time consuming exercise. Following a cost-effectiveness exercise, tree banding could possibly reduce damage to fruit by banded fruit weevil and could also assist in mealybug control by excluding ants from forming symbiotic associations with the mealybugs. Trenches to inhibit banded fruit weevil migration to and from orchards are suggested. By utilising landscaping technology, trenches could be laid down efficiently and at a low cost. Future research in the Western Cape will determine the effectiveness of trenches for weevil control, with the technique so far only having been utilised for control of Colorado potato beetle in the USA.

Host-plant resistance offers growers the opportunity to create systems resilient to damage from certain pests, and cut down on harmful broad-scale insecticide inputs. Resistant strains of apple to woolly apple aphid are being investigated in South Africa, as are strains resistant to other pests abroad. Integration of resistant strains of apple tree with habitat management and diversification could encourage natural enemy activity and reduce pest pressure as a whole. Conversely, inserting insecticidal genes (such as those of Bt) into plants may harm natural enemy complexes and may not be well accepted by consumers.

Novel techniques such as using mechanical vibrations to disrupt insect communication as a means of pest control are being investigated. In this regard no research on Western Cape pests has occurred and this technique is not foreseen to be of any major relevance in the near future.

FUTURE PROSPECTS

There is potential for utilising ‘attract and kill’ for banded fruit weevil as it utilises aggregation pheromones (Barnes & Capatos 1989), but due to difficulty rearing the weevil under laboratory conditions (K. Pringle, pers. comm.), there has been no development in this field. As more is understood about how arthropods communicate, it is likely that pheromones will be isolated from more species and mating disruption could be developed for a number of pest species. Novel techniques require creative thinking and as we learn more about the ecology and biology of pests and their natural enemies, it is likely that completely new approaches to controlling pests will arise. Interrupting the mechanical communication of pests is one such example (Poljanar *et al*. 2014).

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6) Insecticides: Future considerations for deciduous fruit in the Western Cape

ABSTRACT

On-going arthropod resistance to novel chemical compounds used in agricultural pest control is causing growers to consider alternate pest control options. Pressure from consumers and international markets is limiting the number of compounds that can be applied in a season, and how often they are applied. This review considers the driving forces influencing the use of insecticides and acaricides for pest control in agriculture, as we head into a future with more people to feed and more stringent environmental and health legislation. Chemical insecticides are useful components in integrated pest management. However, certain practical management considerations need to be made to reduce the likelihood of chemical resistance developing, so that these insecticides can still be used as a curative measure at times of severe pest outbreak in the future. Spraying alternate rows in orchards and conserving remnant habitats of natural vegetation are examples of how management decisions can increase natural enemy survival, allowing for increased biological control and reduced reliance on insecticides/acaricides alone. More specific insecticides that are non-persistent with low mammalian toxicity and limited negative impacts on non-target arthropods should also be encouraged in the future.

INTRODUCTION

The use of organic insecticides and acaricides (referred to simply as insecticides here) in agriculture for pest control is widespread and requires little introduction. Furthermore, resistance to insecticides by arthropods is well documented and on-going, hence the coining of the term, ‘pesticide treadmill’ (Van Den Bosch 1989). This refers to the development of insecticides, to which arthropods soon gain resistance, hence new chemical compounds are introduced, to which further resistance is established, thus producing a cycle analogous to a treadmill whereby we are constantly trying to run away but gain no distance in terms of long-term control over arthropod-pest populations (Perkins & Holochuck 1993). Unfortunately, natural enemies do not gain resistance as readily as pests do (Croft 1982), thus biological control is reduced in the presence of insecticides (Samways 2005).

With all the negative attitudes surrounding insecticides, it is important to take note that without them, our agricultural systems and food production would probably not have developed to the scale that they have today (Cooper & Dobson 2007). Yet, our dependence on insecticides must be reduced, as we are now realising the negative influence that they have on the environment and human health (Carson 1962). There are alternative means of controlling pests in more environmentally-friendly and health-friendly ways. However, the usefulness of insecticides for application in agricultural and domestic environments as an effective and 'quick-fix' means of arthropod pest-population control cannot be denied (Cooper & Dobson 2007). In order to maintain the effectiveness of insecticides as a fall-back approach, we need to alter our habits and carefully manage the use of these compounds. This review aims to highlight some important management aspects of utilising insecticides and the driving forces that are influencing the extent and use of these compounds as we head into the future. We focus particularly on deciduous fruit production in the Western Cape of South Africa.

PRACTICAL CONSIDERATIONS

In order to conserve vital natural enemy populations, the use of insecticides in integrated pest management (IPM) systems needs to be managed carefully. Calendar spray programmes are not acceptable, as this encourages regular, non-discreet insecticide use which can increase the likelihood of resistance forming (IRAC 2007). Monitoring pest populations is a vital component of pest management and can determine when insecticides are really necessary. Monitoring can also provide useful information on the effectiveness of the pest-control measures in place, and informed decisions are able to be made. If insecticides are absolutely necessary as a control measure, certain management practices can enhance effectiveness, while allowing natural enemies to survive, creating a synergistic effect whereby both biological and chemical control can act simultaneously regarding pest control.

By targeting alternate rows in an orchard, natural enemies are able to find refuge in the unsprayed rows and can continue to contribute towards suppressing insect pests (Weinzierl & Henn 1991), although wind in the Western Cape will complicate effective application of this tactic. The unsprayed rows can then be sprayed at a certain time interval later (depending on the persistence of the chemicals), thereby allowing the natural enemies to have dispersed through the orchard again. Furthermore, on citrus it is feasible to spray individual trees differentially, with applications to the tops of trees allowing natural enemies to be active lower down the tree (Samways 1985). Conserving non-crop vegetation on farm borders and unutilised space can provide areas in which beneficial organisms can reside, benefitting natural enemies and allowing for biological control to take place, post-spray applications (Landis *et al.* 2000).

The timing of insecticide applications is also crucial. Certain insects may be more active at a certain time of day or night for example, thus spraying at this time will increase the proportion of the population that is influenced by insecticides. Non-target organisms need also be considered here, as beneficial organisms such as bees are active when crops are flowering, especially around mid-day, so if application is avoided at these times, non-target organisms may benefit (Gill & Garg 2014). If the phenology of pests is properly understood, the application of insecticides can be timed at the most vulnerable life-stage of the pests (Dent 2000; IRAC 2007). Again, by timing application in this manner, a higher proportion of the target organism can be controlled while minimising unnecessary spray applications. Monitoring practices will be necessary to implement effective timing of insecticide application.

CONSUMER AND RETAILER PRESSURE

A large driving factor influencing the future of insecticides in agriculture is the demand for healthy produce by consumers. Ever since Rachel Carson's *Silent Spring* (Carson 1962), the public have been much more aware of the use of insecticides and the negative consequences on human health and the environment. Retailers respond to this consumer pressure by developing standards that growers need to adhere to. These standards are not only cosmetic but also relate to the use of insecticides in pest control. A South African example of a retailer's response to consumer pressure is the development of Woolworths and WWF's collaboration known as 'Farming for the Future' (King & Thobela 2014). Within this, producers are encouraged to meet certain standards set by Woolworths in order for their products to be acceptable for sale. Standards pertain to food, water and soil quality on farms, as well encouragement to reduce use of synthetic fertilisers, herbicides and pesticides (King & Thobela 2014). This consumer and retail pressure is likely to result in more environmentally friendly practices being implemented on farms, in order for farms to remain competitive and profitable.

Maximum residue levels (MRL) are stipulated for growers that intend on exporting produce from South Africa to certain overseas markets. This defines the maximum amount of chemical (in mg/kg or parts per million (ppm)) that will be accepted on fruit for it to be acceptable for sale in those countries or regions (ABSI 2014; HortGro 2014). If this level is surpassed, exports may be rejected and bans could be imposed. Specific retailers also stipulate a 'maximum number of applications' and a 'maximum number of chemical groupings' that will be accepted (ABSI 2014). The maximum number of applications defines how many times a specific chemical is allowed to be used in a growing season. For example, the insecticide Fenoxycarb may be applied a maximum of 3 times for fruit to be acceptable for TESCO stores (ABSI 2014). The maximum number of chemical groupings refers to the maximum number of different chemicals with different modes of action (MoA) (IRAC 2014) that may be used. The combination of these two regulations limits the amount of insecticide that is available to be used against arthropod pests in a season and is a step towards reducing reliance on insecticides.

The Insecticide Resistance Action Committee (IRAC) has grouped all available insecticides according to their MoA, in order for informed management decisions to be made when utilising these insecticides (IRAC 2014). Resistance in arthropods develops towards the MoA of the insecticide. Thus resistance will form quicker when repeated applications of insecticides from the same group occur that pose the same selection pressure on the arthropod population (IRAC 2014). It is important to utilise varied chemical groupings in order to effectively manage insecticide resistance. This poses somewhat of a challenge due to the ever-increasingly strict regulations being set by industry on chemical usage. Growers are limited to a small number of chemical groupings and are also confined to the limited number of applications per individual insecticide. What may transpire as a result of these pressures is increased use of accepted alternatives such as biopesticides (e.g. *Cydia pomonella* granulovirus CpGV) and entomopathogenic fungi (EPF) and nematodes (EPNs). Certain commercially available products such as EPNs are not considered as chemical insecticides and thus are not limited by MRLs or maximum applications.

PERSISTENCE

What makes insecticides detrimental to the environment is not necessarily their toxicity, but rather their ability to persist in the environment (Dent 2000). Persistent chemicals travel through trophic levels and food webs, influencing not only non-target arthropods, but also fish, birds, amphibians and mammals feeding on those infected arthropods and their predators (Carson 1962). In an effort to ensure food safety, regulations on the ‘pre-harvest interval’ (PHI) or ‘withholding period’ have been set in the industry (ABSI 2014). This refers to the minimum number of days that must lapse between the last spray of that chemical and the first day of fruit harvest. The chemical compound breaks down to a level that is acceptable for human consumption as this time passes. This may differ for different regions, but generally the strictest PHI will be adhered to ensuring exports will be accepted and crop-safety ensured (ABSI 2014). If a chemical is used and the minimum number of days is surpassed, it should not be accepted for sale in markets, as human health may be at risk. Chemicals that have a short PHI are thus very appealing to farmers as they can be used to control pest outbreaks that may occur at a time close to harvest. These chemicals may be of little concern to human health, but may persist in the environment causing unwanted harm to beneficial insects (J. Kuiper, pers. comm.). Chemicals that persist in the environment are also more likely to cause resistance in the pests (Dent 2000). An example of such a chemical grouping with low mammalian toxicity and thus a low PHI but high environmental persistence is the pyrethroids (*e.g.* cypermethrin: PHI= 14 days, MRL= 0.5mg/kg) (ABSI 2014). The optimum would be the use of chemicals that are not only safe for humans, but also the environment and non-target arthropods.

CONTEXT IN APPLE ORCHARDS

Codling moth, *Cydia pomonella* (L.) is the major pest of economic importance in Western Cape apples. If the chemical control of codling moth can be curtailed, natural enemies will have much greater control over the suite of insect pests in apple orchards (K. Pringle, pers. comm.). Mediterranean fruit fly (Medfly), *Ceratitis capitata* (Wiedemann), is also a serious pest, requiring extensive insecticidal control. The first generation of codling moth eggs is laid on tree branches early in the season, with larvae emerging in early spring after 5-10 days. After hatching, the larva soon bores into fruit where it feeds for 3-6 weeks. The larva leaves the fruit to pupate over wintertime under bark, in crevices or in wounds on the trunk and branches of the trees (Sheard & Kaiser 2001). Adults mate soon after emerging, usually between two days and two weeks depending on weather conditions (Sheard & Kaiser 2001). In the Western Cape, the codling moth can have up to four generations in a season (Riedl *et al.* 1998), thus populations can quickly reach high numbers. The Medfly overwinters as larvae in the soil of alternate crops, such as those associated with citrus orchards or produce home gardens (Myburgh 1964), with adults appearing in spring (Sheard & Kaiser 2001). The adult can disperse long distances (from 1-9 km) (Meats & Smallridge 2007) and populations can increase quickly, completing a generation in about 42 days (Diamantidis *et al.* 2011).

As soon as adult Medfly is detected in monitoring traps, cover sprays are normally applied (Sheard & Kaiser 2001). The sprays used are normally organophosphates (OPs). However, bait sprays such as GF-120 (spinosad-based) can be less harmful to natural enemies and are a preferred and widely used alternative (K. Pringle, pers. comm.). In the case of Medfly, both the adult and larva are susceptible to chemical control. However, the larva causes unwanted damage to fruits and thus adults in early season are the main targets of control. Research has shown the potential to utilise entomopathogenic fungi and nematodes (EPF and EPNs) against fruit flies (Goble *et al.* 2011; Malan & Manrakhan 2009). SIT is also developed and functional against Medfly (Barnes and Venter 2006). If overwintering populations of Medfly can be reduced by EPN application, early season Medfly populations will be much lower, thus techniques such as SIT and 'attract and kill', which are both highly effective at lower population levels, could effectively control Medfly and reduce economic damage. These approaches may also aid in conservation of natural enemies, important for controlling other orchard pests. Unfortunately, EPN technology is not at a standard that is able to effectively control overwintering Medfly at present. However, promising results are being shown in current EPN research (A. Malan, pers. comm.).

In order to control codling moth effectively, an early-season cover spray is applied when codling moth is first detected in traps. Degree-day modelling is used to assist with the correct timing of insecticidal sprays. These sprays include certain insect-growth regulators (IGRs), pyrethrins/ pyrethroids and OP insecticides (Pringle, unpubl.). Damaging OP insecticides such as azinphos-methyl, the use of which is not encouraged by the EU (ABSI 2014), are still being utilised, despite damage to the environment and natural enemies, and despite concerns over resistance. Neonicotinoids, which are arguably to blame for massive bee population declines worldwide and have received widespread scrutiny (Blacquiére *et al.* 2012; Spivak *et al.* 2011), are also being used against codling moth in Western Cape apple orchards (Pringle, unpubl.). A ban was imposed on three neonicotinoids, *i.e.* clothianidin, imidacloprid and thiametoxam, for use in EU states for 'seed treatment, soil application (granules) and foliar treatment on bee attractive plants and cereals' (European Commission 2013), effective 1st December 2013. Whether these three insecticides are still utilised or not by growers in Western Cape deciduous fruit orchards is irrelevant, as other neonicotinoids are still being applied, which have the same MoA and thus put honey bees (essential pollinators) and natural enemies at risk. In order for effective IPM practices to take place, we need to shy away from compounds that have detrimental effects on non-target organisms, allowing natural control of pests to be promoted in the process.

In the case of mite pests, which have the potential to cause substantial economic damage (Pringle 2006), an unintentional introduction of a natural enemy has had positive results (Pringle 2001). Mite control previously relied on extensive acaricide applications. However, since the predator *Neoseiulus californicus* (McGregor) has been present, acaricide applications have been curtailed and biological control is providing sufficient control over the phytophagous mite species, *Tetranychus urticae* (Koch) and *Panonychus ulmi* (Koch) (Pringle 2001). This is a positive advance, as the acaricides that may previously have been used can be stored as a back-up for use if a severe outbreak was to occur in the future.

Monitoring of pest populations is of utmost importance in control programmes. Detailed knowledge of pest life cycles can allow the timing of insecticide applications to be in synchrony with the most vulnerable life stages of the pests. By monitoring, we are also able to assess pre- and post-insecticide application population numbers to gauge the effectiveness of a particular technique over time. This is important for determining whether resistance is occurring and can avoid unnecessary further insecticidal applications.

CONCLUSIONS

It should be emphasised that if used correctly, chemicals still have a place in our agricultural systems, unless another control option can show similar success in terms of 'curing' an outbreak. New classes of insecticides, with novel modes of action run the risk of having arthropods form resistance against them, as has been happening for many years (*re* the 'pesticide treadmill' (Van Den Bosch 1989)). If insecticides are applied with detailed planning, taking into consideration the ecology and behaviour of the target pests and consideration for natural enemy well-being is acknowledged, resistance to the compounds can be prolonged. Alternate forms of pest control such as biopesticides and biological control should form the basis of pest control going into the future, with insecticides being held as useful compounds to be used at times of absolute necessity during severe outbreaks in agriculture. It is likely that consumer and retail pressure will continue to strengthen as the public become more environmentally- and health-conscious, driving producers to use fewer chemicals during fruit production. This will inevitably result in renewed interest in non-chemical pest control measures, as growers are forced to meet the standards set by foreign countries and retailers' specific regulations.

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7) Concluding remarks on pest control in Western Cape pome orchards: alternatives to chemical insecticides

The focus of the first part of this thesis has been on the different pest control options currently available in the Western Cape of South Africa, for use in pome orchards. Each of the sections has been discussed separately and reviewed with primary focus on each technique alone. Although some comments are made regarding the integration of the above techniques, it is necessary to analyse the strengths and weaknesses of these techniques and assess the potential for integrating each of them into a holistic pest control system or an integrated pest management (IPM) framework. This information will feed into the scenario planning technique of part two of this thesis.

Ten factors have been chosen to compare the different pest control techniques that have been discussed. Five of these (above the dashed line in table 7.1) were identified as key factors when comparing the pest control techniques against each other. These are: environmental impact; effectiveness (in controlling the target pest population); integration potential (the ability to integrate with other pest control techniques); resistance potential (the potential of arthropods to form behavioural or genetic resistance to the control technique; sustainability/ perpetuity (the potential for long term success of the technique, taking into consideration all of the other factors). The other factors are: persistence (the relative amount of time that a control agent remains active in the system); optimum target population level (the level of the pest population at which the control agent is most effective); species specificity; form of application (reactive or suppressive) and public perception.

The pest control techniques were separated into biological control (biocontrol); the sterile insect technique (SIT); habitat management; mating disruption (MD); ‘attract and kill’; physical barriers (sticky bands/ trunk barriers and trenches); host-plant resistance (HPR) and chemicals (synthetic insecticides). Where 'variable' is listed as a table entry, differences in the application of the technique or the types of control options within that technique may result in different outcomes. For example, in biocontrol of codling moth, effectiveness is variable as certain natural enemies may have a small influence on the pest population, whereas *Cydia pomonella* granulovirus may cause extensive control in the same species (Lacey *et al.* 2008).

Table 7.1: A comparison of pest control techniques for Western Cape pome fruit orchards.

	Biocontrol	**SIT**	**Habitat management**	**MD**	**Attract and kill**	**Physical barriers**	**HPR**	**Chemicals**
Environmental impact	variable	low	low	low	low	low	variable	high
Effectiveness	variable	high	low	high	medium	high	uncertain	high
Integration potential	high	high	high	high	high	high	high	low
Resistance potential	low	low	none	high	high	none	high	high
Sustainability/ perpetuity	high	high	high	low	low	high	high	low
Persistence	variable	short	long	long	long	long	long	variable
Optimum target population level	high	low	independent	low	low	independent	independent	independent
Species specific	variable	yes	no	yes	yes	yes	yes	no
Form of application	reactive	reactive/ preventative	preventative	preventative	preventative	preventative	preventative	reactive
Public perception	positive	uncertain	positive	uncertain	negative	uncertain	uncertain	negative

From table 7.1, several conclusions can be made. All but one of the techniques have high potential to be integrated with each other and would theoretically work well together in an IPM programme. Synergistic effects may even arise, as is the case with integrating *Trichogramma* parasitoids with the SIT in codling moth *Cydia pomonella* (L.) control (Cossentine & Jensen 2000) whereby the combined effect on the population is more than the sum of the two individual techniques alone. Synthetic insecticides ('chemicals') is the only control measure that has low potential for integration. This is due to the non-specificity of broad scale insecticides, and the negative implications this has on natural enemies and non-target arthropods (Samways 2005). As insecticide applications are still the dominant pest control tactic in modern commercial agriculture, this inhibits the integration of most of the other techniques.

In terms of environmental impact, the only three techniques that do not have a low environmental impact are biological control, host-plant resistance (HPR) and insecticides. Insecticides have a high environmental impact due to their persistence in the environment, contamination and non-target effects. Biocontrol is listed as variable, as there are examples of how introduced natural enemies have switched hosts, causing unwanted, negative impacts on non-target species (Boettner *et al.* 2000; Samways 1997). The characteristics that make natural enemies favourable as control agents are the very same traits that could potentially lead to them becoming invasive organisms (Howarth 2000). HPR can have negative environmental impacts when insecticidal toxins (such as Bt) are incorporated into the crop plant (Altieri *et al.* 2004), rather than utilising plant-borne resistance traits.

The potential for arthropods to gain resistance to control measures is very important in assessing the future of control agents. This is a key limiting factor, since once resistance develops, the technique soon becomes completely ineffective. It is highly likely that resistance will form towards insecticides currently in use and any novel compounds that are to be developed, judging by the history of insecticide resistance. Resistance has already been reported towards mating disruption (MD) by a tortricid moth in tea (Mochizuki *et al.* 2002). Although it was overcome by utilising a new mixture of pheromones, if a particular pheromone compound is continuously utilised in Western Cape orchards, there is a chance that codling moth will develop resistance towards the attractant. In 'attract and kill' systems, insecticides are used as the killing agent. As resistance develops to insecticides in general, these killing agents would become ineffective too. Alternative killing agents are being investigated (Peck & McQuate 2000), such as the use of entomopathogenic fungi (EPF) and nematodes (EPNs), as well as Spinosad (insecticide derived from the bacterium *Saccharopolyspora spinosa* (Mertz and Yao)). Habitat management and physical barriers run no risk of genetic resistance forming against them. Host-plant resistance (HPR) has a high risk of resistance forming, due to the very fact that trees remain in orchards for a long while, allowing for arthropods to develop resistance mechanisms. Biocontrol and SIT both have a low chance of resistance forming. Resistance is not ruled out with these techniques, as behavioural avoidance has been reported in each of them (Koyama *et al.* 2004; McInnis *et al.* 1996; Zichová *et al.* 2013).

Effectiveness is ultimately the primary goal of a pest control technique. It is important to note that while some techniques may not bring pest populations down to acceptable levels as stand-alone methods, their integration may work together in creating a 'holistic approach' (Dent 2000). SIT has high effectiveness as it has succeeded in eradicating insect populations in the past (Vargas-Teran *et al.* 2005), and has also shown its effectiveness in the Western Cape (Barnes & Venter 2006). Insecticides are also highly effective. However, resistance causes insecticides to become ineffective and the high likelihood of further resistance forming towards insecticides should not be treated lightly. Resistance management techniques are essential to preserve these useful compounds (IRAC 2007). The effectiveness of biocontrol was listed as variable as the different techniques within (predators, parasitoids and pathogens) each show different results towards different pest species. Parasitoids and pathogens generally show medium to high levels of control, while predatory insects generally provide a medium level of control over pests. Some host-specific parasitoids such as the Trichogrammatidae rely on finding their hosts (in this case codling moth) to survive and thus prove to be very effective control agents (Hassan 1992; Wahner 2008). Habitat management is listed to have low effectiveness as a direct means of pest control. However, the 'push-pull' technique is highly effective and can be considered a type of habitat management tactic; although a holistic push-pull system has not yet been developed in pome orchards. Habitat management encourages a healthy agroecosystem and promotes conservation biological control, as well as strengthening plants' ability to resist pest damage. These are indirect forms of pest control, albeit very important ones in the system as a whole. 'Attract and kill' methods provide a medium level of control over pests. Although 'attract and kill' methods have shown great success elsewhere (El-Sayed *et al.* 2009), the effectiveness against codling moth has been limited in Western Cape orchards (K. Pringle, pers. comm.). Baits are, however, being widely used to suppress Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann). MD is widely used in Western Cape apple orchards against codling moth, and has proved to be highly effective (Pringle *et al*. 2003), although use is normally supplemented by insecticide sprays to ensure proper control over codling moth populations. Physical barriers, such as sticky bands, have proved to be highly effective against banded fruit weevil, *Phlyctinus callosus* (Schönherr), (Pryke & Samways 2007), while the effectiveness of trenches against local pests has not yet been tested. The effectiveness of host-plant resistance (HPR) is listed as uncertain, as no tests have been published on HPR towards local pests, although trials are underway (HortGro 2013).

Perpetuity/sustainability is the final of the five key factors identified. This factor was judged on a combination of the above four factors (environmental impact, effectiveness, integration potential and resistance potential), as well as the influence of other characters in table 7.1. Biocontrol, SIT, habitat management and physical barriers are all listed as having high perpetuity and it is likely that a combination of these characters will provide long-term, effective control over arthropod pests into the future, with minimal environmental impact and resistance issues. HPR is also predicted to have high perpetuity as an integrated technique, although the use of genetically modified plants that express insecticidal toxins is not encouraged. MD, 'attract and kill' and insecticides all have been identified as having low perpetuity. This is due to the likelihood of resistance forming, and in some cases, negative public perception and pressure against them. If properly managed though, the life-span of these techniques in Western Cape pest control could be extended. Monitoring for resistance is an essential component here, as is monitoring pest damage levels. All in all, it would be a pity to lose the use of techniques such as MD and insecticides, which are both highly effective control measures.

From here, the information gathered from each of the previous sections and table 7.1 above will be used to draw scenarios on the potential futures of pest control in pome orchards in the Western Cape of South Africa. The focus shifts from the specific details of each of the individual pest control tactics, towards a more holistic view of the deciduous fruit industry and the key social, economic and environmental factors driving change in the system.

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Where we choose to go from here: Drawing scenarios for Western Cape pome fruit production

Thesis Part 2

8) Scenario Planning Methods

INTRODUCTION

“The only thing that is constant is change” (coined by the philosopher Heraclitus). We are living in a time where technological innovation, political, social, economic and environmental stability are in a constant state of flux. In agriculture, the impending threat of climate change has uncertain consequences for growers worldwide (WWF 2014). The Western Cape has been declared as an area that is highly vulnerable to climate change (Midgley *et al.* 2005). Other threats, as a result of globalisation, are the introduction of new invasive species and the damage that new pestiferous species may pose in agriculture (Hulme 2009). Whatever the future may hold, it is in our best interest to be prepared in the best possible way, or face becoming a ‘passive victim of change’ (ScenarioThinking.org 2006). In order to prepare for the future, a technique known as *scenario planning* has been widely adopted across many different disciplines (Amer *et al*. 2013). This technique involves using a structured and creative method of analysing information to depict possible future states, or ‘scenarios’, that could unfold as a result of driving forces at present (Rajalahti *et al.* 2006). Decisions can then be optimised in order to best prepare for change in the future.

Scenario planning was first publicized by Herman Kahn in the 1960s (Kahn & Wiener 1967) and again by Pierre Wack who developed scenarios for the Royal Dutch Shell company’s future in light of the state of the world’s oil reserves (Wack 1985a, b). In 1986 in South Africa, scenario planner Clem Sunter was tasked by the Anglo American Corporation with producing future scenarios for South Africa during the time of Apartheid (Sunter 1996). Their goal was to assess the stability of the country, which resulted in a ‘high road/low road’ pair of scenarios being created. The high road/low road message was spread to tens of thousands of South Africans in an effort to spread hope for the country. The ‘high road’ depicted a state where negotiation could lead to racial equality and a stable nation, while the ‘low road’ scenario depicted the chance of Apartheid worsening, leading to a state of civil war (Ilbury & Sunter 2011). The work of Sunter and the scenario planning techniques outlined in the book, *The Fox Trilogy* (Ilbury & Sunter 2011), are the inspiration for the techniques to be used in this thesis in depicting potential future scenarios for Western Cape pome fruit production. The theory behind scenario planning will be discussed first, followed by a step-by-step plan in the development of scenarios for pest control in Western Cape pome fruit. The implications of these scenarios and the options we face will then be discussed.

What is scenario planning?

Scenario planning is a method of outlining what could happen in the future. Scenario planning does not predict the future or depict what is going to happen, but rather outlines several contrasting possibilities, according to past and current trends and critical driving forces. It is important to note that scenario planning does not rely solely on past events, as these parameters are good indicators of what happened in the past, but may inhibit us from taking into consideration critical factors and driving forces that could transform our future (Miller 2006). Scenarios are not a continuation of past events, but are rather pictures in which we “imagine the unimaginable” (Ilbury & Sunter 2011). We are forced to think outside the box and put aside our prejudices to consider all possible outcomes, if certain conditions were to arise. In fact, it has been shown that there is a direct link between scenario planning and innovation (Sarpong & Maclean 2011). As a result, by assessing the different options we have, we are able to make informed decisions in order to allow a desired outcome more likely to be reached, according to the actions that one chooses to take.

In reality, there are an infinite number of possible future conditions that may arise. In the short-term, we have more clarity as to the likely conditions of the future, but as we look further ahead into the long-term, the ‘cone of possibilities’ widens, and the less certain we become (Amer *et al.* 2013; Ilbury & Sunter 2011) (figure 8.1). By identifying driving forces and key uncertainties, we can establish an ‘inner cone’ (see figure 8.1) in which our scenarios are likely to fall, but with no definite guarantee. This is useful as it narrows the cone of uncertainty and allows us to be prepared for any of the more likely possible future conditions. A strategy (options and decisions) can be developed which optimally will allow us to thrive or succeed no matter which scenario plays out.

The process of scenario planning is very much tailored to the individual or the organisation that is undertaking the task. Several key steps are generally always taken in the scenario planning process. These include: identifying a problem; gathering background information (thesis part 1); determining driving forces; identifying key uncertainties; creating and describing future scenarios; considering options; making operational decisions and monitoring and re-evaluating decisions and scenarios (Amer *et al.* 2013; APF 2014; Ilbury & Sunter 2011; Rajalahti *et al.* 2006). The specific methodology of Ilbury & Sunter (2011) will be used here, and is discussed below.

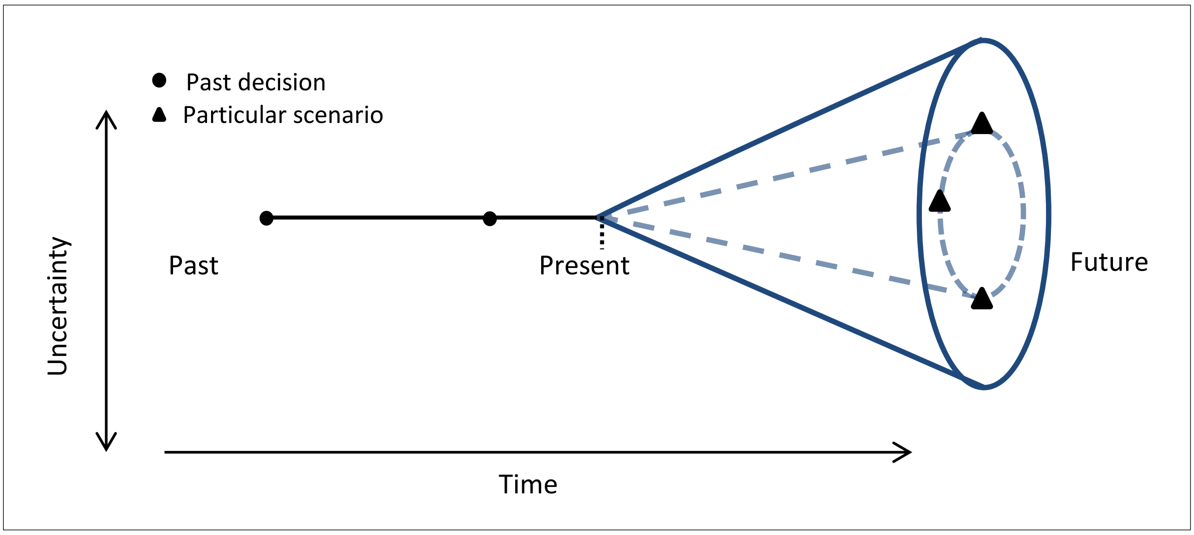

Figure 8.1: The cone of possibility. Adapted from Amer *et al.* (2013) and Ilbury & Sunter (2011)

As scenario planning is not specific to any particular discipline, it can be utilised for any organisation, company, NGO, nation or even individual. With the increasing pressures on food production and the concern over maintenance of biodiversity and delivery of ecosystem services, there is an urgent need to future-proof food production, while maintaining the natural environment for future generations (Samways, unpubl.). I aim to utilise the information gathered in part 1 of this thesis to develop future scenarios for pest control in Western Cape pome fruit orchards. Social, environmental, political, economic, legal and technological driving forces will be considered in developing realistic scenarios. I therefore outline the options the industry has as it moves into an uncertain future.

The purpose of this thesis is to open the minds of growers, researchers and extension officers, and to aid in decision making, rather than actually making the decisions. By developing scenarios of the possible future of pests and pest management in the Western Cape pome fruit industry, strategies can be developed that allow us to be best prepared for whatever may unfold in the future, while considering the importance of food production, human health and environmental well-being. I aim to introduce the method of scenario planning as a useful tool for environmental research. The methodology used here will first be discussed, followed by an in-depth scenario planning exercise using the information gathered from part 1 of this thesis.

OUTLINE OF METHODS

(The methods here are based on those of Ilbury & Sunter (2011))

The analogy of a game is used to describe scenarios and is very applicable here in food production. The production of food is essentially a business and just as sport can have winners and losers, in the food production business, growers can either win or lose money or break-even. This can be extended to the more specific focus of this analysis: pest control in pome fruit orchards, whereby growers are either winning or losing in the management of arthropod pests. By embracing the 'game' metaphor, it allows us to open up our imaginations and 'imagine the unimaginable'.

The conversation model (adapted from Ilbury & Sunter 2011)

This model was developed as an interactive exercise for strategic planning in organisations. The idea is that by generating conversation between all members involved, the most creative and effective scenario building will take place. It is encouraged that this process is undertaken by not only managing personnel in an organisation, but also together with those involved in the front line. For example, in the agricultural setting, researchers, extension officers, as well as growers, farm managers and farm workers should be incorporated into this process. The conversation model will be used as the backbone of the scenario planning process here and has two phases with ten steps in total:

Phase 1: Defining the game

1. Context
2. Scope of the game
3. The players
4. Rules of the game
5. Key uncertainties
6. Scenarios

Phase 2: Playing the game

7. SWOT
8. Options

   ----

9. Decisions
10. Measurable outcomes

In phase 1, the game itself is defined clearly so that all confusion is ruled out. By having a clear understanding of the factors influencing the environment in which we are working, we are most likely to succeed. Phase 2 is the actual implementation of the information from phase 1 into a workable plan and decisions to be taken forward. In this thesis, all of phase 1 is applicable, while in phase 2, steps 7 and 8 are applicable. Steps 9 (decisions) and 10 (measurable outcomes) are beyond the scope of this thesis and should be covered by practitioners in the field, not researchers. It is important to note that these steps are guidelines that have been tried and tested. It is not essential to stick to these steps, as scenario planning is all about adapting to the particular situation at hand. These steps will be followed closely here as they have proven effective in the business environment, but where necessary, I have moulded the steps to fit my particular topic: arthropod pest control in Western Cape pome fruit orchards. Each step is described briefly below.

1. *Context*:

   Refers to the particular game we are playing and all applicable background information. By defining the context, one is able to understand exactly where one fits in to the broader picture, and the role that one fulfils as a ‘player’ in the particular game. The context here is covered by part 1 of this thesis.

2. *Scope of the game*:

   Refers to one’s specific focus area within the game. This feeds on from defining context and simply refers to the range of pest control options that are considered applicable, the area of concern and the key issue to be solved. Scope of the game is also covered in part one of this thesis, where the background information is outlined.

3. *The players*:

   Refers to all stakeholders involved, from researchers to workers to the general public. Anyone at all who may be influenced or have an influence should be considered here.

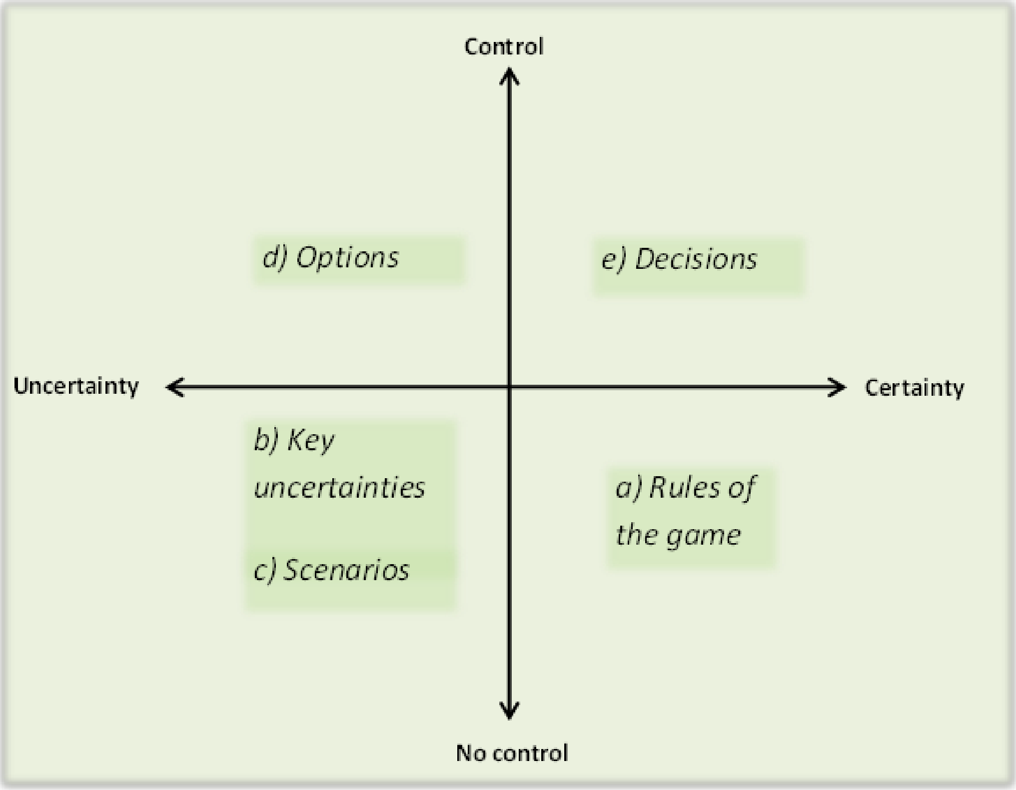

Figure 8.2: The 'Foxy Matrix' adapted from Ilbury & Sunter (2011)

The ‘Foxy Matrix’ (figure 8.2) is a basic outline of a scenario planning technique developed by Ilbury & Sunter (2011). The four quadrants represent how much certainty and control we have over a particular factor, and are useful in outlining what we should focus on, after realising that certain aspects are out of our control and must be accepted (for example, the fact that we have nocturnal and diurnal cycles). It is important to take note and understand what we do not have control over (the ‘rules of the game’ and ‘key uncertainties’), before we move on to the factors that we can control and that we can manipulate to suit our needs (‘options’ and ‘decisions’). The matrix was initially developed and utilised in facilitation workshops by Ilbury and Sunter, but was expanded into the ‘conversation model’ which is outlined (in adapted form) here. Thus, a combination of the two techniques (the ‘foxy matrix’ and the ‘conversation model’) will be utilised to develop the best possible results in this scenario planning process.

4. *Rules of the game (see figure 8.2a)*:

   These are factors that must be abided by in order to 'win the game'. They apply to life, sport, business and almost every endeavour we pursue. Rules may be written or unwritten rules, and apply to all scenarios. These are factors which are certain, and over which we have no control. Although rules are out of our control, what we do about them and how we respond is fully within our control. Rules can be separated into three categories: descriptive, normative and aspirational rules. Descriptive rules are the laws under which one operates and the regulations and standards that one has to adhere to. Normative rules are what we 'ought to do' (Ilbury & Sunter 2011). Ethics, the environment, health, safety and corporate social responsibility are covered by normative rules. Aspirational rules are those factors which one should abide by in order to create a winning strategy. There are normally only a few key aspirational rules, but these give an individual or organisation the winning edge over everyone else. For example, an aspirational rule for growers would be the ability to effectively deal with new pest invasions.

5. *Key uncertainties (see figure 8.2b):*

   These are the drivers of change that we must take note of, moulding the future. These can also be labelled as driving forces. There is always a chance of unexpected key uncertainties arising, causing change, that we must be prepared for. Key uncertainties are uncertain factors over which we have no control. Sometimes a key uncertainty can gradually become accepted as a rule of the game, as it becomes more and more of a certainty in everyday situations. All uncertainties/driving forces should be listed in the scenario planning process, and then narrowed down to the ones most influential to the project and issue.

6. *Scenarios (see figure 8.2c):*

   Possible future scenarios can now be drawn up, using the tools from the previous five steps. Both negative and positive scenarios must be considered, without personal prejudice. It is important to coin catchy names for scenarios, in order for them to stick in peoples' minds and so that people can relate to them. Normally two critical uncertainties are used to create four scenarios (the extreme case of each critical uncertainty is normally used). This will become more clear later though the implementation of these steps.

7. *SWOT:*

   A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is normally done on the organisation or business itself. In the case of this research, a SWOT analysis will be applied to the pest control options, in order to weigh them up against each other. The strengths and weaknesses represent internal factors, relating to the pest control options themselves, while opportunities and threats refer to external forces that influence the individual pest control options.

8. *Options (see figure 8.2d):*

   Once the scenarios have been developed, we now look at the options we have to deal with the future scenarios. What action can we take that will best prepare us if any of the scenarios was to arise? We can look at what options we have to lead us to a desired scenario, by assessing the information we have gathered and looking closely at the rules of the game and key uncertainties likely to drive change. The impact and probability of the scenarios arising should be considered carefully when weighing up ones options. Options are within our control, but are uncertain.

9. *Decisions (see figure 8.2e):*

   Options are considered and a strategy is decided upon from the available options. This is the actual implementation of action. It may be beneficial to assign a time-scale to the project (short or long-term) and set milestones. Progress can be monitored as time passes. As the future is uncertain and change is inevitable, further options must be considered and new decisions made again in time. This is the most effective way to be successful, and adapt to a changing environment. Decisions are factors we are certain over and over which we have full control. Decisions will not be covered in this project.

10. *Measurable outcomes:*

    As the cone of uncertainty widens over time (figure 8.1), it becomes increasingly difficult to predict the success of decisions in the long-term. It is therefore necessary to monitor, in the short-term, the influence that decisions have had on the issue at hand. In the case of pest control in pome fruit, monitoring of pest damage, as well as environmental and human health, are indicators that could be monitored over time to assess how the pest control options that we are implementing are performing. As time passes by, a longer-term picture will be drawn on the effectiveness of the decisions that were made. In the case of sustainable agricultural practices, there is no ‘winning’ or ‘losing’, but rather a balance that needs to be maintained between environmental and human health, food production and economic viability. As conditions change over time, the process of considering different options, and making new decisions will have to be taken. This is similar to ‘adaptive management’ whereby we learn from our implementation of plans and create a dynamic strategy which is continuously updated. Measurable outcomes can only really be decided upon once decisions have been made and therefore they will not be discussed further here.

The above steps, from 1-8, are used in the following section to develop potential future scenarios for arthropod pest control in Western Cape pome fruit orchards.

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9) Developing future scenarios for pest control in Western Cape pome fruit production, and general thesis conclusion

Methods adapted from Ilbury & Sunter (2011)

Phase 1: Defining the game

Step 1: Context

Both context and scope of the game (Step 2) are intertwined. One asks the questions, "What game are we playing? Where do we fit in? And are there any important considerations to mention here that may significantly affect the game we are playing?" (Ilbury & Sunter 2011)

The game I am concerned with is the production of pome fruit in the Western Cape Province of South Africa. The Western Cape is home to one of the world's biodiversity hotspots, the Cape Floristic Region (CFR) (Manning 2008). The region boasts a vast diversity of plant species, many of which are endemic (Manning 2008), thus we have a responsibility to preserve this fragile region. Apple fruit production covers an area of approximately 22 000 hectares in the heart of the CFR (HortGro 2013b). It is essential that environmentally-friendly farming practices are pursued in order to have as little impact as possible on the surrounding environments.

South Africa predominantly exports its pome fruit, with the majority going to the UK and other African countries (HortGro 2013b). In doing so, strict phytosanitary requirements need to be met for exports to be accepted. Consumers also demand blemish-free fruit, thus disease and pest management are mandatory in this industry. A factor that is becoming increasingly more important for growers is the international pressure to align with conservation targets. The Sainsbury's 20 by 20 goals are one such example (Sainsbury's 2013), while the Aichi Targets are another (CBD 2010). In order to align with these targets, there is a demand for healthy produce and responsible environmental practices. This brings me to *Step 2*, the scope of the game.

Step 2: Scope of the game

Scope of the game can be considered as 'a snapshot of current activity'. "How do we want this [snapshot] to look in several years time?" (Ilbury & Sunter 2011).

In order to align with international conservation targets, provide consumers with blemish-free fruit and meet phytosanitary standards, there is a need for effective, environmentally-friendly arthropod pest control. The key focus of this project is to seek out environmentally-friendly techniques for controlling arthropod pests in pome fruit production, in the Western Cape of South Africa. The techniques (scope of the game) are covered in detail in the first part of this thesis, as is a more detailed discussion of Western Cape pome fruit production (the context of the game) in general.

Step 3: The players

"[In sport], if you are to win the game, you need to know as much as possible about the people playing in the same game." (Ilbury & Sunter 2011)

In business settings, the above statement is very applicable, as business is naturally competitive. Growers can also be viewed as businessmen. However, the specific scope of this project is the assessment of environmentally-friendly techniques for arthropod pest control. It is still necessary to list the key stakeholders (players), as many people and organisations are influenced by, or influence the pest control options utilised by growers in the field. The actions and views of key stakeholders can have a large influence on the uptake of the different pest control technologies. For example, consumers are generally not in favour of the widespread use of chemical insecticides on fruit, thus retailers (such as Sainsbury's) have implemented strict regulations (such as maximum residue levels) that growers need to adhere to in order for produce to be acceptable for sale in their shops. This illustrates how players across the globe can influence how the game must played here.

Ilbury & Sunter (2011) recommend categorising the players into three categories, depending on whether the particular stakeholder is for or against your strategy, or whether they are neutral and could swing for or against you at different times. The key stakeholders in environmentally-friendly methods of arthropod pest control are listed as:

For

- Consumers
- Retailers
- NGOs (*e.g.* WWF)
- Biological control companies/producers
- Organic growers

Against

- Chemical companies

Neutral

- Farm workers
- Growers
- Producer organisations
- Exporters
- Researchers
- Scenario planners
- Pest control officials
- Government
- Media
- Chemical companies

The stakeholders listed in the 'For' category are all fully supportive in the search for more environmentally-friendly methods of controlling arthropod pests. Retailers depend on consumers to survive, thus retailers follow consumer trends. The latest trend, and necessity in order for food production to be sustained into the future, is for environmentally-conscious, and health-conscious farming methods to be encouraged. Biological control companies would benefit if growers were to rely more on the use of natural enemies, as the market for mass-reared predators and parasitoids would increase. Organic growers are required to adhere to certain protocols in order to retain organic certification. Any advances in non-chemical methods of pest control would be welcomed by organic farmers, whether they are certified organic growers or not, as these methods align with the values of these farmers.

Stakeholders listed in the ‘Against’ category are those that do not support the search for environmentally-friendly pest control techniques. The only stakeholder listed here is chemical companies. Chemical companies are however, also listed as ‘neutral’. The reason for this is that chemical companies manufacture massive volumes of synthetic pesticides which are sold globally every year (Osteen 1993). Any tactics that do not rely on chemical compounds, such as biological control and the SIT for example, are in direct competition for sales that the chemical companies could have made in terms of insecticides. Thus, chemical companies would most likely encourage growers to use different compounds that they produce, in order to maximise their profits (they are also players in a game, trying to win just like anyone else). The upside is that chemical companies have large amounts of capital which in some cases are now being devoted entirely to research and development of alternative pest control technologies, such as the use of biological control. Certain companies are offering growers not only the option of chemicals, but also products such as entomopathogenic fungi and nematodes (Becker Underwood 2014). In these instances, chemical companies would be in support of environmentally-friendly pest control techniques, hence their placement in the ‘neutral’ category too.

The other players in the game could swing either way depending on the circumstances. Growers want the most effective pest control techniques in order for produce to be blemish-free and marketable in high-end retail outlets across the world. They will utilise the most effective methods, in terms of cost and pest-population control, whether they be chemicals or not. At the same time, however, retailers and regulations are forcing growers to seek out alternative methods to chemical pest control (ABSI 2014). These different factors influence growers’ position in the game. Another player worth mentioning is the media. The media are the ‘watchdogs’ of the world (Ilbury & Sunter 2011), and can expose positive or negative activities to the public. The media can be very influential on creating opinions amongst consumers and depending on the situation, work for or against the aims of promoting environmentally-friendly pest control techniques. It is not necessary here to list the specific situations in which the listed stakeholders would be for or against the aims of this project, but rather to be aware of all the listed stakeholders and their general position (for, against or neutral) in this game.

Step 4: Rules of the game

"How you act in accordance with the rules is within your control, whereas the rules themselves are part and parcel with the game." (Ilbury & Sunter 2011)

If one refers to the foxy matrix (Chapter 8, figure 8.2), one can see that the rules of the game are situated in quadrant 'a', in which elements are certain, and over which we have no control. Rules are important to understand in order to succeed in the game. In pest control in pome fruit, many different variables are influencing how we operate. These are listed under three categories: descriptive, normative and aspirational rules. Rules of the game apply to all scenarios.

Descriptive Rules (What we have to adhere to)

- Pest populations must be kept at a level in order to prevent damage
- Maximum Residue Levels (MRLs)
- Maximum number of chemical groupings for application on crops
- Maximum number of applications of chemicals
- Standards to be met in terms of fruit appearance, size and shape
- Phytosanitary pests must be controlled
- Pre-harvest Interval (PHI) of chemicals must be adhered to

Normative Rules (What we ought to do)

- Farm worker safety ensured
- Persistence of harmful chemicals in the environment should be minimised
- Target specificity should be high, and non-target organisms should not be harmed
- Control options should not harm crop plants
- Beneficial organisms (natural enemies; pollinators) should not be harmed
- Align with conservation targets (Sainsbury's 20 by 20; Aichi targets; WWF 'farming for the future')
- Socially accepted methods should be followed
- Economic viability

Aspirational Rules (Rules to win the game)

- Provide effective, cheap, long-term environmentally-friendly pest management
- Resistance to chemicals should be effectively managed and curtailed
- Integrated pest management (IPM) strategies should be followed
- Monitoring of pests is essential
- Pest control methodologies should be able to integrate with each other fully
- Ability to deal with new pest invasions effectively
- Incorporate adaptation management strategies

Step 5: Key uncertainties

"Surprises that may necessitate a change in strategy or tactics" (Ilbury & Sunter 2011)

In the case of environmentally-friendly arthropod control, there can be many factors with the potential to drive change in the way one operates. Key uncertainties can be grouped as social, technological, environmental, economic, or legal. In figure 8.2b (Chapter 8), we can see that key uncertainties are uncertain factors that are out of our control. However, the steps we take to alleviate the impact of uncertainties are within our control. A key uncertainty may have a low or high probability of occurring and will also either have a low or high impact on our strategy in controlling arthropod pests in pome fruit. A number of key uncertainties were identified in an IPM meeting held by growers, researchers and extension officers in the Department of Conservation Ecology and Entomology on 12th April 2013. These, along with other key uncertainties that I have identified, have been listed according to their category, and numbered for easy reference (see figure 9.1).

Environmental

1. New pest invasions
2. Resistance
3. Climate change (including extreme weather and water availability)
4. Plant disease
5. Soil health

Economic

6. Fruit price
7. Cost of pest control techniques
8. Price of energy and fuel (influences pesticide price)

Social

9. Labour issues (strikes/wages etc.)
10. Change in consumer preference
11. Media attention

Legal

12. New legislation (MRLs; PHIs; trade barriers)
13. Human health and safety

Technological

14. New pest control techniques

Figure 9.1: Fourteen identified key uncertainties driving change in Western Cape arthropod pest control (in no particular order)

Key uncertainties either come about gradually or they may arise suddenly and have a great, unexpected impact. In order to draw scenarios to prepare for these otherwise unexpected changes in driving forces, one needs to identify a small number of key uncertainties on which to base the scenarios. The method suggested by Ilbury & Sunter (2011) and also discussed by Amer *et al.* (2013), which will be used here, is to identify two key uncertainties that will have the highest impact on the strategy and that have the highest probability of occurring. Identifying which two uncertainties to use is optimised by plotting a graph of probability vs. impact (PI graph) (see figure 9.2), and placing the listed uncertainties within the matrix. Assessing the impact and probability of occurrence of each of the uncertainties is carried out by reviewing the context and scope of the game, the background research and by consulting with experts in the field. The probability is not exact, but rather a relative position on the graph, in relation to the other uncertainties. It is important to keep a level of flexibility when drawing up the PI graph, as the reality is that we do not really know what is going to happen and when. We only know which key uncertainties are more likely to occur and which key uncertainties will have a relatively large impact on our strategy in arthropod pest control.

In figure 9.2, it is clear that key uncertainties 1 (New pest invasions), 2 (Resistance to insecticides) and 12 (New legislation) (all circled) will have the greatest impact and are the most likely to arise. As resistance and new legislation appear the most likely to occur, these two critical key uncertainties will be used to draw scenarios of possible futures. This choice was also made on the premise that if one uncertainty outside the player's control and one within the player's control are chosen, it makes the scenarios easier to grasp as it gives the players some ability to influence their destiny (Ilbury & Sunter 2011). In contrast, when two external uncertainties are used to develop scenarios, players are at the mercy of fate and can only adapt to a certain extent, which can result in scenarios being harder to grasp. Both new pest invasions and changes in legislation are external to growers. Resistance to insecticides is somewhat controlled by our actions and resistance management practices (see chapter 6). Thus 'resistance' and 'legislation' will be used to draw up possible future scenarios, while new pest invasions and other key uncertainties will be discussed where applicable in the scenario descriptions. A few key uncertainties that could also have a high impact are worth discussing further here first.

Both climate change and the cost of pest control technologies (3 and 7 respectively, in figure 9.1 and figure 9.2) will have a relatively high impact on our ability to control arthropod pests. Climate change is a gradual threat, which can increase the chance of extreme weather events such as heat waves, droughts, floods, and hail, all of which will negatively influence the growth of fruit and could make trees more susceptible to disease and pest damage (Aurambout *et al.* 2006). Changes in climate will also influence the distribution of pests (Parmesan 2007) and will likely increase the risk of new pest invasions occurring (Thomson *et al.* 2010). On top of all this, a shift in climate could bring about unsuitable growing conditions for pome fruit, and halt the industry altogether (Midgely & Lötze 2008). As a gradual threat, we need to monitor the signs of climate change, and ensure that necessary efforts are taken to prevent it having major influences on the deciduous fruit industry.

The cost of pest control techniques could increase (or less likely, decrease) suddenly which would force growers to make tough business decisions. To remain profitable, the most effective and cheapest control options are most likely to be chosen, but would the options chosen be the most environmentally-friendly and those most likely to provide long-term control?

The lowest region of the PI graph (figure 9.2) is labelled 'wild cards' as these are uncertainties on which we do not have a lot of information, that could suddenly arise and have large impacts on our strategy. One uncertainty which is believed to be unlikely to materialise is a change in consumer preference (position 10 on figure 9.2). Although unlikely to occur, a sudden change in consumer preference, or worse, a boycott of the industry would result in limited to no sales, and hence a collapse altogether. Another uncertainty, although not mentioned in the PI graph is land claims. This political uncertainty is a real threat to farmers in South Africa. If farms are repossessed and change ownership, the influence on arthropod pest control is really up to the new owners, that is if the farms are even maintained for fruit production at all.

The key uncertainties listed would all likely have varying impacts on arthropod pest control. A lengthy conversation could be held discussing all of the listed driving forces. However, the real drivers of change are those identified in the top right region of the PI graph: changes in legislation, resistance to insecticides and the introduction of new invasive pests. The crux of the future will be shaped by these, hence the focus of discussion will be on these uncertainties, but where applicable, the other uncertainties will be discussed in the respective scenario descriptions.

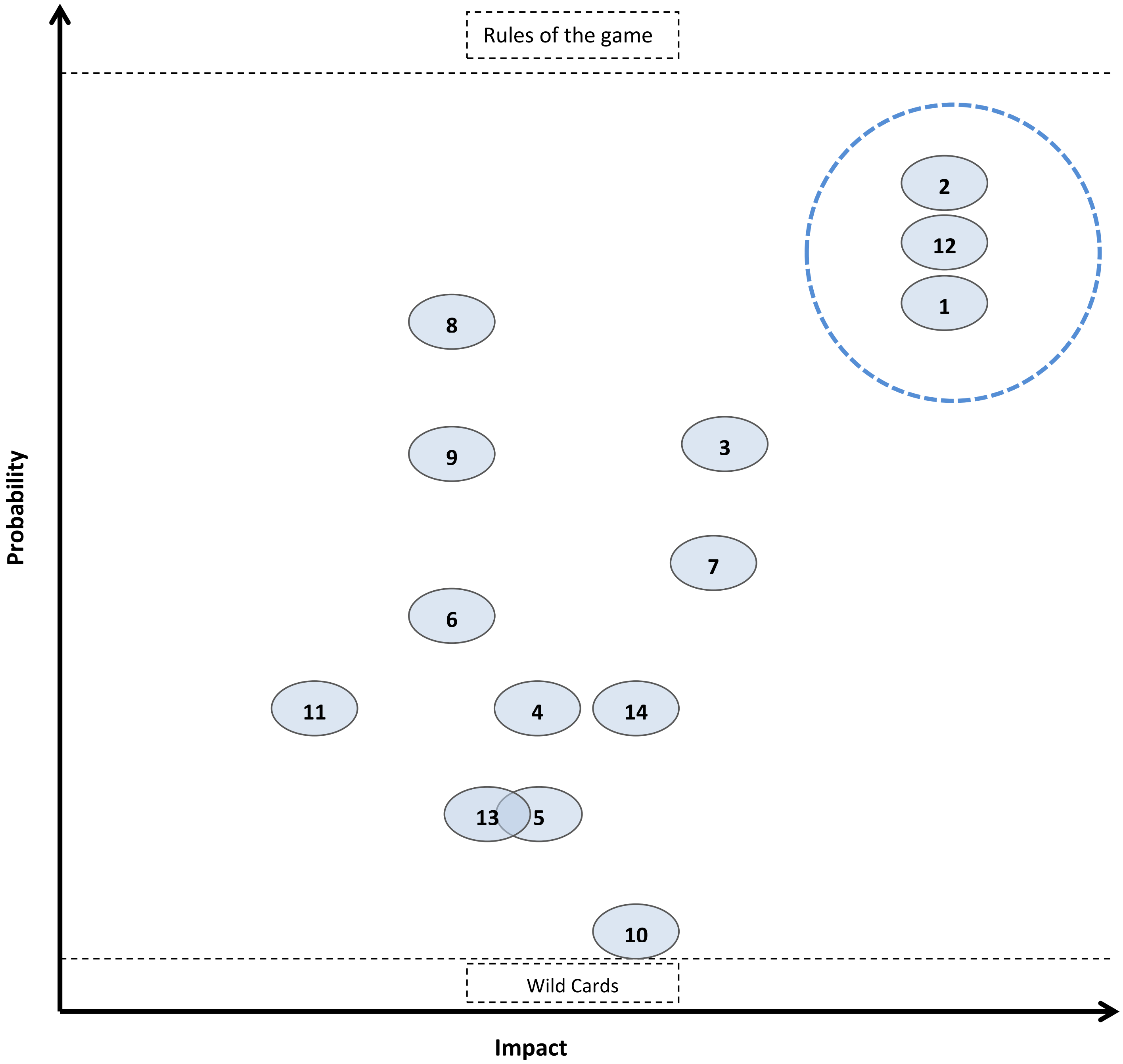

Figure 9.2: The general probability vs impact of the key uncertainties arising and influencing arthropod pest control in Western Cape pome fruit. This is only a rough measure, in order to identify the critical key uncertainties (circled).

Key:

1. New pest invasions
2. Resistance
3. Climate change
4. Plant disease
5. Soil health
6. Fruit price
7. Cost of pest control techniques
8. Price of energy and fuel
9. Labour issues
10. Consumer preference
11. Media attention
12. New legislation
13. Human health/safety
14. New pest control techniques

Step 6: Scenarios

“Scenarios help to depict what future environments will look like, as well as define the capabilities required in order to succeed in any scenario” (Ilbury & Sunter 2011)

A 4x4 matrix (figure 9.3) is used here to visually depict four possible future scenarios, driven by changes in legislation and arthropod resistance to synthetic insecticides. According to Ilbury & Sunter (2011), scenarios are received better by readers if the descriptions are not overcomplicated and if names are catchy, indicating the essence of each scenario. After all, we are uncertain of the exact parameters of the future, but intend on rather depicting scenarios that are believable and that are based on a balance of reasoning and intuition after assessing our current environment in terms of rules and uncertainties.

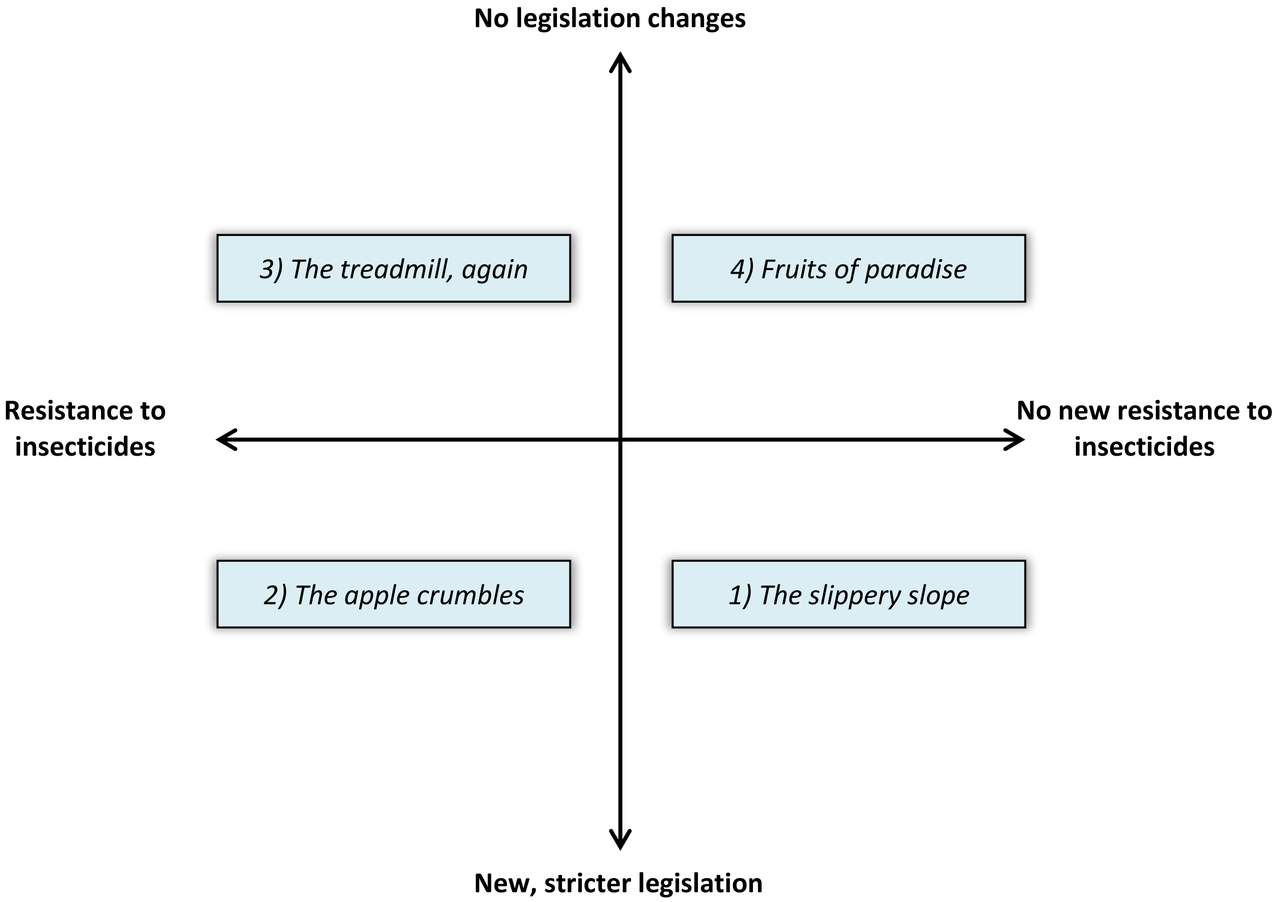

Figure 9.3: The scenario matrix, showing the four possible future scenarios as driven by the extremes of two key uncertainties, ‘resistance to insecticides’ and ‘legislation’.

Painting a picture: describing the scenarios

<u>Scenario 1:</u> ***'The slippery slope'***

(No new resistance to insecticides; new, stricter legislation)

Pressure from consumers and environmental groups causes a change in regulations with regard to maximum residue levels (MRLs), pre-harvest intervals (PHIs) and the number of chemical groupings permitted per season. This has a large impact on famers, since in order to continue to export produce to high-end markets and meet phytosanitary standards, the arthropod pest damage must still be kept at a minimum, but with a very limited array of insecticidal options. Fortunately, the available chemicals are still effective as the arthropods are still susceptible and have not yet formed resistance. Some permitted chemicals would have to be used more than in previous years due to new restrictions on other chemical groupings. This would encourage resistance to form as utilising the same mode of action repetitively is a direct driver of resistant populations forming (IRAC 2014). This is an unstable state as growers sit on the edge of a slippery slope between effectively controlling pests with limited chemistry and pests being likely to gain resistance, increase in population size and cause unacceptable damage. In the mean-time, consumers would be blissfully unaware of the risk to the fruit industry and would readily purchase fruit which retailers would continue to market as 'environmentally-friendly' due to their top-down approach of driving change by enforcing stricter standards. While pests are still susceptible to chemicals, this would be a good time for biologically-based pest control to be implemented, investing in further research and development of techniques such as SIT, pheromone based disruption and habitat management, to ensure that pests are effectively controlled before any resistance to chemicals does arise as a result of ineffective resistance management practices, driven by the stricter legislation on insecticide usage.

<u>Scenario 2:</u> ***'The apple crumbles'***

(Resistance to insecticides; new, stricter legislation)

In the event of stricter legislation being enforced and a simultaneous rise in arthropod resistance forming, 'the apple crumbles' will result. Arthropod populations rise to uncontrollable levels, causing widespread damage above economic thresholds. In response, growers turn to the once-effective chemical insecticides to bring populations down, but to no avail. These chemicals are now useless and happen to also infringe on new laws and regulations set that limit chemical use to an absolute minimum. Growers can transgress these laws in a feeble attempt to control pest outbreaks, and face bans on exports to most regions or give up all together, cash-in and sell off their farms to more ambitious developers hoping to exploit the views of the surrounding mountains by building luxurious security-estates. One option would be to accept a certain amount of damage, cut down on costs of pest control and settle for lower prices offered by the processed food industry, but this may not be a very attractive option. Growers in this scenario find themselves stuck between a rock and a hard place (or an apple and an indestructible codling moth). They may as well cover costs by baking apple crumble from what can be salvaged, to sell at local markets.

On a more serious note, the introduction of new invasive arthropod pests in this scenario would cause widespread destruction and be near impossible to control, if growers were too reliant on chemical control as a long-term solution in the past. Options such as integrated control of pests and habitat management may have prevented this scenario from being reached. However, hindsight is a foe to growers at this point.

<u>Scenario 3:</u> ***'The treadmill, again'***

(Resistance to insecticides; no legislation changes)

If arthropods develop resistance to the chemicals currently in use, but legislation remains as it is, growers will have the opportunity to control these rising pest populations by utilising certain chemicals, still permitted by regulations and that may still be effective against the pests. However, cross-resistance in arthropods (whereby resistance to several chemical groupings occurs at once) is common, and growers may be left with very few viable control options in terms of chemical insecticides. The use of biological control and other alternative techniques such as SIT, pheromone based disruption and habitat management could save growers some time before the next resistance event occurs, which would most likely be a severe case to which almost all chemicals prove ineffective. This scenario would be a repetition of the pesticide treadmill described by Van Den Bosch (1989), and a continuing arms race between arthropod pests and insecticide development would ensue. This would continue, meanwhile consumer and retailer pressure would mount due to concerns over environmental and human health, increasing the likelihood of stricter regulation being enforced on the already-dwindling supply of chemical insecticides. This unstable scenario could soon reach a state of desperation whereby resistance is unmanageable and growers run the risk of shifting into '*the apple crumbles'* scenario. Introduction of new invasive pests into this system would not be handled positively as these pests would possibly be resistant to chemical control too, as a result of improper resistance management in their country of origin, resulting in the organism slipping through phytosanitary checks.

Scenario 4: ***'Fruits of paradise'***

(No new resistance to insecticides; no legislation changes)

If no new cases of resistance occur, and legislation on chemical usage remains the same, a harmonious scenario is possible. The '*fruits of paradise'* would be a best-case scenario for growers and consumers alike. Farms here incorporate habitat management to encourage conservation biological control and increase crop and soil health, resulting in a system resilient to pest invasion. Sustainable control techniques have been implemented and well integrated, that work synergistically in keeping arthropod pests below the economic threshold. Any outbreaks in pests, which would likely be prevented by the healthy system in the first place, are controlled by utilising selective insecticidal applications, which are still permitted by legislation and remain functional thanks to effective resistance management. New pest invasions may cause initial disruption, but can be controlled through natural enemies already in the system and by further insecticidal applications, where necessary, to bring initial population numbers down. Growers acquire high-prices for fruit as exports are accepted by foreign markets and practices are aligned with those of conservation targets (such as Sainsbury's 20 by 20 (Sainsbury's 2013) and the Aichi targets (CBD 2010)). Consumers are able to purchase fruit that is grown in a manner that respects both human and environmental health. This system is also more resilient against the gradual threats of climate change and the complications that arise with it. This system would be favourable and sustainable in the long-term, especially as the changes brought about are from a bottom-up approach and implemented by farmers and not as a result of a top-down approach whereby legislation and 'shock-events' (such as resistance or new invasions) drive changes in grower practices.

Phase 2: Playing the game

Now that the relevant factors in our environment have been assessed and used to draw possible future scenarios, we need to look at our own practices and assess the options we have in order to deal with any of the future scenarios in the best possible way. By carefully analysing our options, we can make decisions and implement action to prevent ourselves from slipping into the worst-case scenario, '*the apple crumbles*', and strive towards reaching a sustainable future: '*the fruits of paradise*'. The information gathered in the first part of this thesis will be used here to conduct a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis on each of the pest control techniques. From there, the options we have in front of us today will be discussed.

Step 7: SWOT (Strengths, weaknesses, opportunities, threats)

Strengths and weaknesses are within our control, whereas opportunities and threats are external factors, influencing how we act. In order to succeed, we must accept our strengths and weaknesses and capitalise on our opportunities in order to mitigate our threats. In the concluding chapter (chapter 7) of the first part of this thesis, a table (table 7.1) was used to compare the different pest control technologies against each other in terms of ten parameters. Table 7.1 provides us with the necessary information in analysing the strengths and weaknesses of each technique. Some of the opportunities and threats relating to each pest control technique have been identified already, while assessing the key uncertainties in previous steps. In order to analyse the SWOTs of each technique, a table (table 9.1) has been used here again , as this is the clearest depiction of the necessary information. The SWOT analysis in table 9.1 will help in discussing which options are the most practical and which do not offer much hope.

Table 9.1: SWOT analysis of pest control tactics

Tactic	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Biocontrol	• High integration potential • Low resistance potential	• Research and management intensive • Can result in environmental contamination • Effectiveness variable	• Stricter legislation on chemical usage favours the use of biologicals • Not affected by chemical legislation	• Climate change • Widespread use of broad-scale insecticides
SIT	• Low environmental impact • High effectiveness at low pest populations • Species specific	• Mass-rearing and sterilisation diminishes insect quality and performance • High start-up and maintenance costs of facilities	• Not influenced by chemical legislation • Integrated control programmes benefit from techniques effective at low pest-population density	• Growers do not see the necessity of SIT • Lack of funding
Habitat management	• Sustainable in long-term • Provides many benefits to agricultural system, including resilience to pests and disease	• Low effectiveness at directly controlling pests (besides ‘push-pull’ technique)	• Wide encouragement to conserve diversity encourages diversification of farms and implementation of habitat management	• Natural vegetation is wrongly-perceived to encourage pest outbreaks • Not perceived as necessary by growers in general
Mating disruption	• Highly effective • Species specific • Increasing effectiveness as pest-populations decrease	• Negatively influences pheromone-based monitoring techniques • Requires a large number of pheromone dispensers	• Can assist in reducing insecticide applications for major pests such as codling moth	• Strong winds in Western Cape can reduce effectiveness • Resistance may form to pheromones used

Tactic	Strengths	Weaknesses	Opportunities	Threats
Attract and kill	• Species specific • Attracts pest to the killing agent, thus less agent required compared to regular insecticides	• Use of chemicals to which resistance is forming	• Use of entomopathogenic fungi and nematodes as killing agents	• Negative public perception (use of chemical killing agents) • Resistance to insecticidal component would render technique ineffective
Physical barriers	• Species specific • Low environmental impact • No resistance potential	• Labour intensive	• Stricter legislation on chemical usage favours the use of non-insecticidal techniques • Opportunity for research into effectiveness of trenches against weevils in orchards in Western Cape	
Host-plant resistance	• High integration potential • Resilience against pest attack • Long-term option	• Insecticidal genes in some HPR cases can negatively influence non-target organisms • Not developed for pome orchards in South Africa	• Not yet developed in South Africa, thus opportunity for research and development	• Public concern over genetic modification of crop plants
Synthetic Insecticides	• Highly effective (in absence of resistance) • Curative measure • Effectiveness independent of pest-population numbers	• Non-specific • Environmental contamination • Low integration potential • Can negatively influence human health	• Resistance can be managed by intelligent use and integration as part of biologically based pest control systems	• Resistance forming • Legislation limiting use • Negative public perception

Step 8: Options and thesis conclusion

The vision of the Aichi biodiversity targets states: 'By 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people.' (CBD 2010)

There are three excerpts that I would like to emphasise in the mission statement of the Aichi targets (CBD 2010):

1) '…ensure that by 2020 ecosystems are resilient and continue to produce essential services…'
2) '…biological resources are sustainably used…'
3) '…appropriate policies are effectively implemented, and decision making is based on sound science and the precautionary principle.'

In reviewing our options for the challenge of controlling arthropod pests in pome fruit in the Western Cape, it is now essential to re-evaluate our aims and to review the scenario planning process that has just been undertaken. It is in our best interest to strive towards an agricultural system that is able to produce healthy food for generations to come while simultaneously conserving our natural heritage, taking into consideration human and environmental well-being. This aim, if fulfilled, would align with the mission statement of the Aichi biodiversity targets outlined above, as well as the values of Sainsbury's (Sainsbury's 2013) and local high-end retailers such as Woolworths (King & Thobela 2014). In order to maintain market access to important European regions, we need to consider the options we have in front of us carefully, in deciding which route we take into the future. The rules of the game and key uncertainties are once again, critical in our decision making process. Three pertinent questions raised by Ilbury & Sunter (2011) are considered at this stage of the process:

1) What options do we need to consider in achieving greater compliance with the rules of the game, specifically the rules to win (aspirational rules)?
2) Can the challenges faced by the key uncertainties be met?
3) How can we strive towards the best-case scenario and is it possible to avoid the worst-case scenario altogether?

The rules of the game are split into three categories, descriptive, normative and aspirational. When assessing our options, any options that do not comply with the descriptive rules are out of the question as these have to be adhered to. Options should comply with all the normative rules, although non-compliance will still allow us to operate, but would be to our own detriment. The aspirational rules are important considerations here. In order to strive towards the best-case scenario, the '*fruits of paradise'*, we need to choose options that best encapsulate the aspirational rules. At the same time, we need to be aware of the risk vs. reward of deciding to take any of the particular options.

It is evident that more biologically-based pest control techniques need to be pursued as the majority of the descriptive rules relate to conforming to regulations that limit chemical insecticide usage. It is mandatory that pest populations are controlled and damage is kept to a minimum. In order to do this, pest control options need to be effective. We need to accept that in order to maintain effective pest population control in the long-term, it is unlikely that one control option alone will suffice. Rather, the integration of techniques into holistic integrated pest management programmes is essential (Dent 2000), in which resilient agricultural systems are formed, as stipulated within the Aichi Targets (CBD 2010).

An option we have is to enhance the resilience of orchards by integrating beneficial plant species between orchard rows, as well as conserving natural patches of fynbos on farm borders and unutilised spaces (Gaigher & Samways 2010). By doing so, this will encourage natural enemy populations, which will provide a permanent level of resilience against pest outbreaks (Nicholls & Altieri 2004). Not only will conservation biological control be encouraged, but the health of trees and soil is likely to be favoured too, as beneficial intercrop species can aid in offering nitrogen to surrounding plants (Pretty 2008), while organic matter can improve disease control in soil due to the presence of beneficial microorganisms (Addison *et al.* 2013; Altieri & Nicholls 2003). By favouring soil and tree health, orchards' ability to resist disturbance events is likely to be enhanced, which may be favourable in light of the risks that climate change (and its associated effects) poses. Conserving habitat diversity within orchards will also aid in the conservation of biodiversity in the Cape Floristic Region (CFR), allowing for a mosaic of natural vegetation across transformed agricultural landscapes. Most species diversity in the world does not occur within protected areas (Rodrigues *et al.* 2004), thus it is important to soften the contrast between natural and disturbed areas (such as agricultural land) in order for the movement of species and gene-flow to be conserved (Samways 2005). Habitat management also fulfils several aspirational criteria, *i.e.* the ability to deal with new pest invasions (resilience) and is it an integrated strategy that offers a cost effective contribution towards long-term, environmentally-friendly pest control. Whichever scenario arises, striving towards a healthy orchard environment through habitat management will be beneficial and should be taken forward as a decision to be followed through with.

As habitat management is not a direct form of pest control, other options need to be pursued as well that ensure pest populations are kept at low levels to prevent fruit damage. The likelihood of resistance to chemical insecticides is high, as is the likelihood of stricter legislation on chemical usage as consumers push for better environmental practices and healthy produce. Thus, in aligning with the mission of the Aichi biodiversity targets, we must base decisions on 'sound science and the precautionary principle' (CBD 2010) and our reliance on chemical insecticides needs to be curtailed, otherwise we face slipping deeper into the worst-case scenario, labelled here as '*the apple crumbles'*. The other control options labelled with high affectivity (besides insecticides) in table 7.1 include sterile insect technique (SIT), mating disruption (MD) and physical barriers. Another two not specifically listed in table 7.1 include the 'push-pull' technique and certain specific biocontrol practices. Two of the focus species of this study demonstrate the point, *i.e.* the use of *Cydia pomonella* granulovirus (CpGV) and parasitoids against codling moth (*Cydia pomonella*) have proven to be very effective (Hassan 1992; Wahner 2008), while entomopathogenic fungi and the integration of parasitoids with SIT have proved highly effective against Mediterranean fruit fly (*Ceratitis capitata*) (Castillo *et al.* 2000; Ekesi *et al.* 2002; Réndon *et al.* 2006; Wong *et al.* 1992). These two pests are of major economic importance and require several insecticidal applications per season and if they can be controlled effectively without harmful chemical insecticides, natural enemy and parasitoid survival and effectiveness in controlling other pests will be raised.

The push-pull technique, although not developed as a holistic technique in pome orchards to my knowledge as of yet, holds great potential as a long-term pest control option. It is a perfect example of how integrating knowledge from differently focussed disciplines can work together synergistically to achieve a common goal. Technology from MD, habitat management and biological control are combined to form a system resilient to attack, by deterring pests away from the crop and attracting them into areas in which they can be controlled biologically or by selective insecticidal application (Khan *et al.* 2011). Research and development into push-pull techniques in Western Cape pome fruit orchards should be of utmost importance as a viable, long-term, environmentally-friendly pest control technique.

By first creating a resilient landscape through orchard habitat management, biological control will naturally increase. However, inoculations with key biocontrol agents such as Trichogrammatidae parasitoids (for example, the indigenous *Trichogrammatoidea lutea* (Girault), a parasitoid of not only codling moth, but bollworm, *Helicoverpa armigera* and apple leaf roller, *Lozotaenia capensana* as well) and CpGV sprays for codling moth, and Braconidae parasitoids along with entomopathogenic fungi for Mediterranean fruit fly are essential. In this way, growers will not have to be concerned about infringing upon legislation relating to chemical usage, which could previously have limited access to certain export markets. Resistance to chemical insecticides can be managed effectively by utilising these biological options, thus allowing chemicals to be withheld as back-up options for times of severe outbreak pressure, to be used only when really necessary. This strategy is well demonstrated in biological control of mites in Western Cape orchards which has already replaced acaricide applications (Pringle 2001).

The SIT has been mentioned here as a highly-effective control measure. This is true. However, we must be aware of the limitations facing this tactic. The only facility rearing and sterilising codling moths for release in SIT programmes in the Western Cape was closed down as of the end of 2014. This, despite the effectiveness and potential of the technique for long-term, species-specific pest control, was due to growers' unwillingness to support the programme financially. This is not surprising, as current pest control techniques are proving to be effective enough to see farmers through each season. However, as we look at the possible future scenarios, it is highly likely that further resistance to insecticides will form, and new stricter legislation on maximum residue levels (MRLs), the number of chemicals groupings used and the number of insecticide applications, will be drawn up. In order to prevent a future situation in which we are left with very few effective and permitted insecticides, I feel it is of utmost importance to capitalise on the SIT as a technique for controlling codling moth and Mediterranean fruit fly. As an option, it fits in with the descriptive, normative and aspirational rules of the game, thus putting us in good stead on the path towards '*the fruits of paradise*'. Admittingly the cost of the technique is high, and cannot be ignored. Government subsidy helped the area-wide SIT programme to succeed in British Columbia, Canada (Vreysen *et al.* 2007). However, the likelihood of a similar situation occurring in South Africa is uncertain.

One of the aspirational rules of the game includes the importance of a pest-control tactic being able to provide effective and long-term control over pests. Perpetuity (table 7.1) is listed as high for all pest-control tactics, except for mating disruption (MD), 'attract and kill' and insecticides. MD has proven to be a very effective tactic in preventing codling moth population numbers from increasing in orchards (Bloemfield 2003; Pringle *et al.* 2003) and is widely used across the Western Cape. As a non-disruptive, species-specific method of pest control, MD is a great means of reducing insecticide applications (Brunner *et al.* 2002). There has been a case of resistance to the MD tactic by a tortricid moth in tea plantations. However, resistance management techniques can ensure that resistance does not form to pheromones used (Mochizuki *et al.* 2002). Mating disruption is a very positive technique for integration with other pest control technologies, although its limitations must be recognised and provisioned for (for example, its limited effectiveness on orchard boundaries and in hilly landscapes).

‘Attract and kill’ techniques should theoretically provide a more effective means of control over pests than MD. However, uptake in the Western Cape, especially against codling moth, has been limited. Bait sprays continue to be widely used for Mediterranean fruit fly, but the use of insecticides as killing agents pose the risk of the methods becoming ineffective as the likelihood of resistance forming to these killing agents is high. An option worth pursuing is the use of entomopathogenic fungi (EPFs) and nematodes (EPNs) as the killing agents, rather than insecticides (Peck & McQuate 2000). These options offer an environmentally-friendly approach, and could increase the sustainability of ‘attract and kill’ methods by avoiding the issue of resistance formation. Although ‘attract and kill’ methods are mostly species-specific, the use of insecticides is still viewed in a negative light by consumers, thus viable alternatives such as the use of EPFs and EPNs should be considered in this tactic. ‘Attract and kill’ tactics have high potential to be integrated with other tactics, thus making them valuable in IPM programmes. However, the issue of resistance to this technique must be addressed for it to be a viable option in the long-term.

Judging by the likelihood of resistance and new, stricter legislation becoming reality in the future, any techniques that are able to control pests with no insecticidal input are favourable. The use of physical barriers such as sticky bands, which inhibit banded fruit weevil, *Phlyctinus callosus,* from reaching tree canopies, have shown to be highly effective (Pryke & Samways 2007). The advantage with such a technique is that resistance will likely never form to its mode of operation. It has no negative environmental impact and is independent of pest-population size, with the added advantage of integration potential within IPM programmes. The cost of labour may make application of tree-bands unattractive, however, in light of future scenarios, sticky tree-bands may prove to be essential components of orchards. Trenches have been successfully used to control Colorado potato beetle *Leptinotarsa decemlineata* in Canada (Boiteau *et al.* 1994), and there is potential that a similar exclusion barrier could effectively reduce banded fruit weevil populations in Western Cape orchards. By inhibiting migration in and out of orchards, plastic-lined trenches are another environmentally-friendly method of pest control with potential for long-term application in orchards worth pursuing, in light of potential future scenarios.

A large amount of research interest has focussed on developing host-plant resistance (HPR) to pests, particularly in annual crops (Altieri *et al.* 2004). HPR either involves breeding for a particular resistant form of the plant, or the insertion of insecticidal genes into the host-plant genome is undertaken. The latter can be very effective, as is the case with Bt crops, in which *Bacillus thuringiensis* is incorporated into crops (Altieri *et al.* 2004). This carries many environmental risks though, including arthropod resistance to the tactic, and is not welcomed by consumers (Altieri *et al.* 2004). Utilising HPR can aid in reducing insecticide applications (Phipps & Park 2002), thus its risks vs. rewards must first be considered before implementing the tactic. In pome orchards, no HPR is yet recognised to any of the major economic pests. However, research is being conducted into the use of apple trees resistant to woolly apple aphid. *Eriosoma lanigerum* (HortGro 2013a). Choosing HPR that poses little to no risk to the environment and non-target organisms is of utmost importance in succeeding in the long-term management of arthropod pests.

In order to be best prepared for the future, no matter which scenario is to arise, we need to be prepared for shock-events, particularly the invasion by new pestiferous arthropod species in agriculture, as well as the gradual threat of climate change and its associated affects. Due to globalisation and the massive amount of trade between continents across the world, the risk of new invasions is high (Hulme 2009). We must consider the key uncertainties outlined and assess which options will best prepare us should any of the high-impact uncertainties become reality. From the literature reviewed in this thesis, it is clear that a holistic, area-wide integrated pest management (AW-IPM) approach needs to be taken forward into the future. We need to manage our orchards as agroecosystems, rather than production lines, and consider landscape rather than farm-scale approaches. A diversified system is less susceptible to new pest invasions and disease compared to simplified, monocrop systems (Altieri 1999; Gurr *et al.* 2004; Nicholls & Altieri 2004; Root 1973). Agroecosystems also improve soil and plant health, creating resilience to disturbance in crops and reducing the need for external inputs such as fertilisers and insecticides (Hargrove 1991; Nicholls & Altieri 2004). By first recognising the importance of soil health, and environmental and ecosystem integrity, we can manage orchards that are inherently resilient rather than susceptible to damage. In doing so, management of the orchard environment will require a thorough knowledge of the pests and associated natural enemies in the system. Monitoring is absolutely essential to ensure that pests are controlled and to assess the influence of pest control technologies on pest population numbers. By implementing effective orchard sanitation practices, and monitoring pests populations, effective management decisions can be made that ensure natural enemy survival is paramount and that pest control options are chosen with the aim of long-term suppression, that do not compromise the health of humans or the environment.

If we recognise the importance of our choices today, and the influence that these will have on the agriculture of tomorrow, we can strategize to ensure that the best-possible scenario is reached. The decisions to be made should take into consideration the future scenarios outlined in this thesis, and the rules and uncertainties that pertain to all scenarios. The options for arthropod pest control have been outlined and discussed here, but the decisions remain in the hands of growers and extension officers. A scenario planning exercise such as this is an important exercise that allows us to take a step back, and observe the game in which we are involved. It is essential that in practice, the final two steps: decisions and measurable outcomes are covered. By doing so, it gives the scenario planning activity purpose and allowso for the process to be held again, when necessary, to re-evaluate performance, and to re-assess options and make further strategic decisions. By engaging in a conversation approach like this, we are able to view the world as it really is, and not how we perceive it to be through our own clouded spectacles. The value of this cannot be stressed enough, whether it be for planning the approach to arthropod pest control in Western Cape pome fruit, or be it in our personal lives. I would like to end with a quote: “No sensible decision can be made any longer without first taking into account not only the world as it is, but the world as it will be” Isaac Asimov (Ilbury & Sunter 2011).

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