Knowledge review of agroecological crop protection approaches in vegetable production systems to reduce pesticide use

Report written for A Lighter Touch

September 2022. Report number 1-2022

Merfield Agronomy Ltd.

Permanent Agriculture and Horticulture

Research, Consulting and Extension

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Citation Guide

Merfield, C. N. (2022). Knowledge review of agroecological crop protection approaches in vegetable production systems to reduce pesticide use. Report number 1-2022. 58.

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1. Summary

A Lighter Touch (ALT) aims to understand, implement and demonstrate agroecological approaches to crop protection to reduce agrichemical pesticide use across the horticultural and arable sectors.

This report gives an overview of the agroecological approaches to manage arthropod pests, plant pathogens (diseases) and weeds (henceforth just 'pests') in New Zealand vegetable production systems, to achieve agrichemical reductions.

The report provides the basis to demonstrate some of the techniques at two vegetable production sites, one in Pukekohe and the other in Canterbury.

Due to the many crop species grown on vegetable farms, and the much larger number of species of pests across all the crops, and the many agroecological techniques to manage them, this report can only give an overview, not give detailed prescriptions to be directly implemented. Rather it aims to inform and inspire growers to start experimenting with some of the ideas in their own systems and be a roadmap for future research projects for the New Zealand vegetable sector.

The main techniques and issues covered in the report are:

- The three forms of biological control, introductory (classical) conservation and augmentation, the latter which includes the biopesticides.
- Conservation biocontrol is particularly relevant for arthropod pest and weed management.
    - For arthropods increasing plant diversity in and around the production system is key to provide resources for beneficial insects that can keep arthropod pests below economic thresholds.
    - For weeds, using beneficial plants to out compete 'true' weeds.
- Integrated pest management (IPM).
- Management of non-cropped areas.
- Rotations.
- Intercropping, particularly strip cropping.
- Subsidiary crops and their sub forms including, cover crops, smother crops, green manures, catch crops, living mulches, trap crops and biofumigation crops.
- Mesh crop covers for arthropod and vertebrate pests.
- Minimising weed seed rain.
- False seedbeds.
- Mechanical weeders.
    - Contiguous weeders, e.g., spring tine harrow.
    - Incontiguous weeders, e.g., interrow hoe and intrarow weeders.
    - Robotic weeders.
- Nutrient placement.
- Plants vs. weeds – subsidiary crops including overwinter cover crops and living mulches.

Many techniques can be used to manage multiple pests at once as well as other benefits such as improving soil health, and increasing the robustness and resilience of vegetable systems, particularly in the face of increasing extreme weather events.

2. Introduction

A Lighter Touch (ALT, a-lighter-touch.co.nz) aims to understand, implement and demonstrate agroecological approaches to crop protection to reduce agrichemical pesticide use across the horticultural and arable sectors.

Within ALT a sub-project aims to demonstrate agroecological management of pests, pathogens, and weeds in vegetables, with a focus on onions, on-farm at two sites, one in Pukekohe and the other in Canterbury. These aim to demonstrate to growers a range of agroecological techniques and encourage them to trial and implement them on their own properties. This has the wider aim of assisting growers reduce their use of, and dependency on agrichemicals.

This report describes the key agroecological approaches to pest, pathogen and weed management in vegetables. This is intended to be a direct source of information for growers about the kinds of agroecological techniques they could employ. However, due to the high level nature of this report, the large number of agroecological techniques across the weed-pest-pathogen management spectrum, and the limited agroecological research in vegetables it is impossible to give detailed instruction to address specific problems. Rather this report aims to show the breadth and depth of possible approaches to inspire growers to try their own approaches and resources to further information sources.

2.1. Terminology

A number of common and not so common terms are used in this report. This section briefly defines the terminology used.

Agroecology is a century old science that studies agriculture through an ecological lens and undertakes agri/horticulture with an ecological system based mindset. It does not just cover ecological approaches, it includes all aspects of production, such as machinery and pesticides. See fao.org/agroecology/home/en/ for more information.

Pest is used in the broadest meaning, and includes arthropods (insects, spiders, mites etc.), pathogens (diseases), nematodes, molluscs, vertebrates, viruses, weeds etc. Where specific pests are discussed, e.g., fungi, their particular name is used.

Beneficials, **biological control (biocontrol) agents** (BCA), and **natural enemies** are used interchangeably depending on context. They all mean 'good' organisms that attack 'bad' i.e., pest species. Good organisms are not just restricted to arthropods, but include all species, such as microbes and vertebrates.

SNAP is an acronym for **S**helter, **N**ectar, **A**lternative prey / hosts and **P**ollen (see section 2.1 for details). SNAP is part of conservation biocontrol (see section 3.1). The term '**floral resources**' is sometimes used in the wider literature to describe the **N**ectar and **P**ollen component of S**N**A**P**. However, the use of the term is avoided in this report, see section 2.2.

Cash crops are those that are grown to produce a cash income. **Cover crops**, **non-cash crops** and **subsidiary crops** are alternative names for crops grown other than to produce a cash income (such as improving soil health, managing weeds). Cover crops is the most commonly used name globally, particularly North America. There are also multiple sub-types of cover crops (which are described in the cover crop section 3.6). However, there is no agreed usage of the term 'cover crops', and the term is used to describe some of the sub approaches, for example, in Europe the term 'cover crop' is often used to describe what are also called 'living mulches' under perennial crops. The term 'subsidiary crop' most accurately describes the role of 'cover crops' / 'non-cash crops', and has no other meanings or baggage. It is also increasingly being used in the EU. 'Subsidiary crop' is therefore the term used in this report.

Biopesticides are direct biological alternatives to the agrichemical pesticides (see section 3.1). They are mostly based on microorganisms, such as bacteria and fungi which attack the pests, and are typically applied with an agrichemical sprayer.

Interrow is the space between the crop rows and **intrarow** is the crop row.

Control vs. **management:** linguistically and attitudinally the concept of pest **control**, i.e., complete elimination, has changed over the last few decades to pest **management**, i.e., keeping pests within manageable (economic) limits (see IPM 3.2). However some terms, such as biological control, are so engrained that the old terminology persists.

Taxonomic names are given for all species except crop plants. They are also given at every instance of the common name, unless in the same paragraph, so readers do not have to look through the whole report to find the taxonomic name. The genus is also always given in full, i.e., not abbreviated, again so readers do not have to search for them.

2.2. Agroecology cv. conservation biocontrol cv. floral resources cv. SNAP

Within the ALT team working on this project there has been a focus on 'floral resources' for arthropod pest management. Often this is within the SNAP concept. However, SNAP is just a part of conservation biocontrol, which itself is just one of three types of biocontrol - introductory (classical), augmentation and conservation. Biocontrol in turn just one of a multitude of pest management techniques within agroecology. Floral resources and SNAP are therefore only a tiny part of agroecological pest management. It is therefore important that the project broadens its focus from the narrow target of floral resources and SNAP to the much wider vision of agroecology.

2.3. Agroecology and system redesign

A key foundation of agroecology is systems redesign based in ecology. This means that to be done comprehensively, the farm system as a whole has to be re-imagined. Mainstream farming and growing has allowed the farm system to be compartmentalised, for example nutrients can be managed separately to weeds, and likewise separately from pathogens. Within a system based approach these different management areas interact, e.g., nutrient and irrigation management impacts weed and pathogen management, weed management impacts arthropod pest management etc. So, while some of the techniques described in the report can be used as compartmentalised techniques, others will be more effective when used as part of system redesign.

Ideally changes to the system will have multiple benefits. For example, planting living mulches under crop plants to protect soil from rain / irrigation drop impact, will also build soil health, fix nitrogen, camouflage the crop from pests, boost beneficial insects that attack crop pests and increase overall biodiversity.

A practical way to understand system redesign is the ESR concept (Hill & MacRae, 1996) (Figure 1).

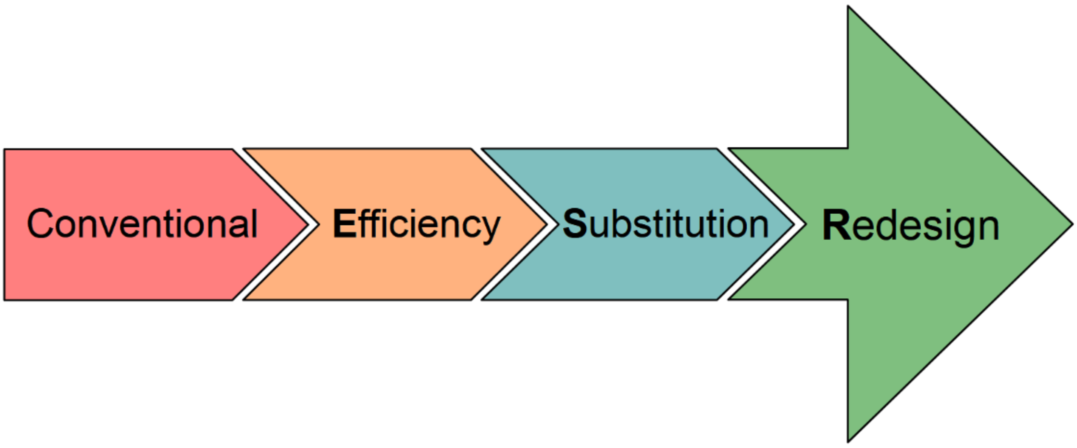

Figure 1. The 'ESR' concept of the path to system redesign (Hill & MacRae, 1996).

Conventional is characterised by the 1970s and 1980s approaches such as calendar spraying (Figure 1).

The 'E' in ESR is for efficiency, represented by approaches such as integrated pest management (IPM) which only applies agrichemicals when pest populations reach an economic threshold and site specific weed management (SSWM) which only applies herbicides where weed plants are growing and not to bare soil.

'S' is for substitution. A common example is substituting mechanical weed management for synthetic herbicides in organic agriculture. Done well mechanical weed management can achieve similar outcomes to herbicides in terms of weed-free paddocks of monoculture vegetables. While this substitution has reduced agrichemical use, the outcomes are still monocultures and bare soil which are ecological undesirable, and no co-benefits (such as pest management or biological N fixation) are achieved through mechanical weeding. Thus, substitution is not the aim of agroecology.

'R' for redesign represents an agroecological approach where the whole system is reconceived and redesigned to achieve multiple simultaneous benefits, mostly through biological and ecological manipulations rather than physical and chemical techniques such as mechanical weeding and herbicides.

The ESR concept therefore acts as both a vision of the ultimate destination of agroecological transformation of the production system, and, also a pathway of how to get there. A considerable change in mindset, extensive new knowledge and experience is required by growers to move to agroecology. Trying to jump from conventional to redesign in a short time is likely to result in significant failures, due to incorrect mindset and lack of understanding of the complexities of ecological management. It is considered better to transform the production system and mindset by moving through all three stages of ESR and treating them as a learning opportunities and also building up the number of tools and expertise than can be brought to bear on problems.

2.4. Knowledge review

2.4.1. Search parameters, issues and limits

A search of the literature was made using multiple approaches including the Lincoln University library general search facility, general web searches, searching agroecological websites (e.g., www.fao.org/agroecology/home/en/), a review of agroecology papers and books owned by the author, searching through reference lists, etc. A key challenge was that due to there being a large number of vegetable crops, a search using the term 'agroecology and vegetables' would miss papers that were specific to one vegetable (e.g., onions) and that did not include the word vegetable in the paper. In addition there are many agroecological techniques (for example intercropping) and papers on individual techniques may not include the word 'agroecology'. Further, there are huge numbers of pests, pathogens and weeds attacking the many different species of vegetables. Many articles, especially reports of experiments, focus on one crop species and on one pest, again resulting in more general searches missing them. Undertaking searches for a specific crop and a single pest would likely yield a larger number of results, but, the number of combinations of all the crops, pests and management technique is vast, such that the time spent searching would be equally vast.

A significant amount of grey literature is in languages other than english. For example France appears to be undertaking a considerable amount of agroecological research in vegetables, for example ecophytopic.fr/recherche-innovation/concevoir-son-systeme/projet-4sysleg and many references are to French language papers. While computer translation of websites generally works well, translation of PDFs, especially larger files with complex layouts is less successful.

The literature on agroecology specifically for vegetables is considerably less than for mixed, arable and pastoral farming. Many techniques for non-vegetable systems are of limited value or incompatible with vegetable production, e.g., no-till and root vegetables.

Agroecological techniques also go far beyond pest, pathogen and weed management. For example, many techniques are focused on soil health and system level changes to the farm, which, are also outside of this review's remit, as it is focused on pest management.

All these issues mean that searching for information on general vegetable agroecology is challenging at best and thus many potentially valuable information sources have not been found. No sources were found that gave a comprehensive overview of agroecological pest management in vegetables. This report may thus be the first to do so. The main structure of this review was therefore based on the author's 30+ years experience in agroecology, including organic and regenerative agricultures. The structure was then populated with more specific examples both from the literature and the authors personal experience.

Of the small number of review papers on vegetable agroecology the following may be valuable for readers wishing to gain a deeper understanding (Wezel *et al.*, 2014; Malézieux *et al.*, 2018; Puech *et al.*, 2021; Rizvi *et al.*, 2022).

2.5. Market specifications often work against agroecological and biocontrol approaches

A key challenge noted in a number of sources was that market specifications and requirements are a significant barrier to the uptake of agroecological practices in vegetable production (Lefèvre *et al.*, 2020; Puech *et al.*, 2021). While addressing these issues is outside the remit of this report and associated project, this issue needs to be raised in wider forums.

2.6. Applicability of overseas research

The applicability / direct use of overseas research is confounded by the unique nature of New Zealand's production ecosystems. Virtually the entire New Zealand farming system is imported (i.e., exotic), principally from northern Europe - all the crops, all the livestock and all the pests (broad meaning). The few exception include native arthropods that have become pests, (such as grass grub (*Costelytra zealandica*) and lemon tree borer (*Oemona hirta*)). However, large numbers of species (both beneficials and pests) are absent from New Zealand that are found in the countries where New Zealand's farming systems originate. This is clearly beneficial when the 'missing' species are pests, but, not when they are natural enemies of pest species that are present in New Zealand. Some overseas research will include species (beneficial and pests) that are absent from New Zealand. This is particularly pertinent for field research where there is no control over the species present, for example research on conservation biocontrol. This means techniques that work well overseas, may completely fail in New Zealand due to the absence of key species.

New Zealand also has a quite narrow range of climates, and mostly young and volcanic soils, while a large amount of agroecological research is undertaken in the tropics and other climates and soils quite different to New Zealand. This limits the direct applicability of such research to New Zealand.

Overseas research should therefore be re-tested under real-world conditions in New Zealand before being recommended for use at scale, on farm.

3. General agroecological techniques for pest management

There are a considerable number of agroecological techniques that operate at the system level or they can be used for management of more than one type of pest, i.e., weeds, arthropods, pathogens (both soilborne and airborne). These general techniques are described in this section, and then pest specific approaches are described in their own sections.

3.1. Biocontrol: its three forms - importation, augmentation and conservation

Biological control (biocontrol) is a means of managing / controlling pests using other organisms, through the following ecological interactions:

- predation,
- parasitism,
- disease,
- herbivory,
- competition.

Biocontrol is therefore not really biological rather ecological management. Biocontrol is therefore one form of many agroecological pest management techniques. Biocontrol also overlaps with IPM (see section 3.1), particularly augmentation biocontrol (see below). It also applies to all pests, not just insects and the wider arthropods, although that still tends to be its focus. Thus it is covered as a general approach.

Biocontrol is divided up to into three forms, importation, augmentation and conservation.

3.1.1. Importation (classical) biocontrol

Importation biocontrol, commonly called classical biocontrol, is where an organism is taken from where it originated into a new location / ecosystem, where it becomes a pest. This is typically because it's natural enemies are absent from the new ecosystem. Importation biocontrol 'imports' the natural enemy (or enemies) from the pest's original ecosystem to the new ecosystem with the aim that it will regulate the pest. After importation it is then often described as a biocontrol agent. Due to the risk that the natural enemies could become pests themselves, a substantial amount of science is required and well as legal approval. Importation biocontrol is thus almost exclusively the preserve of governments and their agents.

Growers are therefore mostly passive beneficiaries of importation biocontrol, though they can lobby government for new potential biocontrol agents to be imported.

3.1.2. Augmentation biocontrol

Augmentation biocontrol is where the biocontrol agent is already present, but, it's populations are so small that it is failing to keep the pest in check. The numbers of the BCA are therefore augmented. There are two approaches / sub-forms of augmentation biocontrol

3.1.2.1. Inoculation augmentation biocontrol

Inoculation augmentation biocontrol is where small numbers of the BCA are introduced with the aim that they will multiply to sufficiently large population that they will bring down and maintain the pest below economic thresholds. It is therefore mostly used as a preventative technique, with BCA's being released on a regular schedule to ensure their populations are maintained at sufficient levels. If a pest has reached damaging levels, inoculation biocontrol is unlikely to control it. This is the main form of biocontrol used in glasshouse crops against arthropod pests.

3.1.2.2. Inundation augmentation biocontrol

Inundation augmentation biocontrol is where large, often vast, numbers of BCA's are applied / released. This can be used preventatively (prophylactically) to prevent pests reaching economic thresholds as well as remedially to cure pest outbreaks. Most inundative BCAs are microbes (bacteria, fungi) although other organisms, such as arthropods and nematodes are also used. Biopesticides are a form of inundative augmentation biocontrol. Biopesticides can often be used as a direct substitute for agrichemical pesticides, so are a straight forward way to reduce agrichemical use where suitable biopesticides are available.

There are a considerable, and growing number of augmentation biocontrol products. This is in part because augmentation biocontrol products are commercial products, the same as agrichemical pesticides. The downside for growers is they need to repeatably purchase products, just as for agrichemicals, so they are an ongoing production cost.

3.1.3. Conservation biocontrol

Conservation biocontrol is based on manipulating the production ecosystem, both in the paddock and the surrounding area to boost beneficial species with the aim of bringing pests under economic thresholds. Often this is mostly based on increasing plant diversity, such as intercropping (see section 3.5). SNAP is therefore only one approach of many for conservation biocontrol (see section 2.2).

3.1.3.1. Targeted vs. general conservation biocontrol

Conservation biocontrol approaches vary from the highly targeted to a more general, broad brush approach. Targeted conservation biocontrol focuses in on individual pests in one or a small range of crops, develops a detailed understanding of the crop – pest – biocontrol agent ecosystem and then finds specific solutions to boost the BCA and bring the pest under economic thresholds. In New Zealand one of the textbook examples is the Greening Waipara project that manages leafroller caterpillar (*Epiphyas postvittana*) in grapevines by providing nectar and pollen from buckwheat (*Fagopyrum esculentum*) to boost the population and number of eggs laid by the parasitoid (parasitic wasp) *Dolichogenidea tasmanica* during the period when the grape berries are growing. While targeted biocontrol can be highly effective, the large number of crop and pest combinations, especially in vegetable production means that a huge amount of research would be required to address every crop – pest combination one at a time. The alternative is to use a more broad brush approach. This is based on increasing the general plant diversity across the whole farm, both inside the paddocks, and around field margins and even the wider landscape, i.e., agroecological system redesign.

3.1.3.2. Conservation biocontrol – under the growers control

Compared with introductory biocontrol which is the preserve of governments, and augmentation where growers have to repeatedly purchase products to replenish the biocontrol agents, conservation biocontrol has the considerable benefit that it is entirely under the growers personal control. The costs of diversifying the farm system principally with herbaceous (e.g., pasture) species in paddock can be as little as a few tens of dollars of seed and sowing costs per paddock ha which may provide benefits for many years. While planting woody vegetation around paddocks is a larger cost, once established the benefits should last for decades. Conservation biocontrol therefore offers the grower the maximum control and return on investment of all the biocontrol systems.

3.2. Integrated pest management (IPM)

Integrated pest management (IPM) in this context applies to all pests, such as weeds and pathogens, not just arthropod pests which IPM is most commonly associated with.

IPM is founded on the concept that pest management is fundamentally an economic activity. Pests reduce yield which reduces income which reduces profit. Pest management incurs costs (such as buying pesticides, and the cost of spraying) so if the cost of management is larger than the increased return resulting from pest management, undertaking management is economically irrational. For example if pests will reduce crop returns by $500 / ha but $1,000 is spent on management then the grower has incurred a $500 / ha loss. Clearly the wider impacts of pest impacts need to be taken into consideration, e.g., aphids may not be a direct problem but may spread viruses. But fundamentally pest management is about increasing profit.

IPM is based on a setting economic action thresholds for each pest species. This often requires scientific research to determine and is therefore not undertaken by growers, rather industry bodies or research organisations undertake this work.

The challenge in vegetable production (compared with arable and glasshouse production systems) is the much larger range of crops and pests, plus the more diverse range of environments means that the cost and work involved in setting economic thresholds for all but the most common crops is impractical. Market quality requirements, such as zero tolerance for any arthropods, pest or beneficial, in produce is another barrier, as noted in section 2.5. While this may limit the ability to implement IPM in vegetable production systems, the concept is still considered highly valuable, and therefore worthwhile growers building it into their mindset.

Once an economic threshold has been set the following three step process is used.

1. Monitor pests on a regular basis – typically weekly to fortnightly,
    - Below economic threshold take no action,
    - Above economic threshold take action,
2. Use most benign / least harmful management methods first, see Figure 2,
3. Monitor results of treatment to confirm they have been effective.

Repeat steps 1 to 3 throughout the production life of the crop.

In terms of using the most benign / least harmful management methods IPM uses the concept of the four management toolboxes (Figure 2).

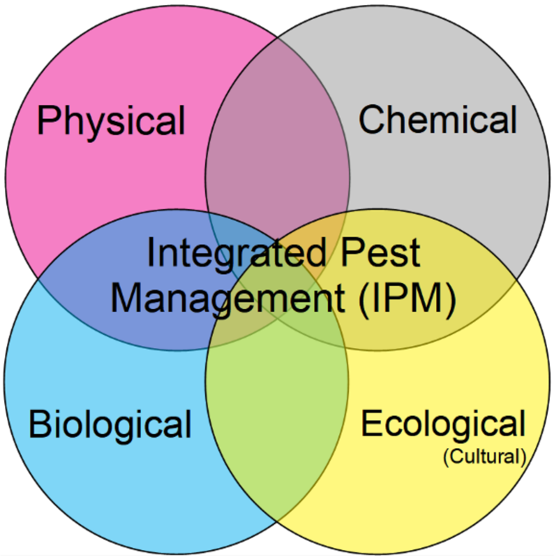

Figure 2. The four integrated pest management toolboxes.

Examples of physical management techniques include mechanical weeding and mesh crop covers. Chemical management means agrichemical pesticides, i.e., herbicides, fungicides, insecticides etc. Biological and ecological management as terms are often interchangeable, but, both refer to management techniques that rely on biological controls and ecological approaches such as living mulch. Some descriptions of the IPM toolboxes use 'cultural' as an alternative to biological and ecological.

The aim is to use biological and ecological management approaches as a first resort, as they are the most agroecological, and then physical as the next option and keeping chemical management as a tool of last resort. This order of use does not just apply to IPM but for all pest management approaches.

IPM thus overlaps with biocontrol (section 3.1) in that biocontrol approaches, particularly augmentation biocontrol, can be used as an IPM management tactic.

A few definitions of IPM are much broader and include preventative measures, such as conservation biocontrol. Most however use the description used above. Within this report, IPM is presented as the more common reactive definition as per the three steps above.

3.3. Management of non-cropped areas and alternative hosts

Non-cropped areas around production paddocks, e.g., fencelines, tree rows and the wider landscape can have large impacts on beneficial species in crops (Landis *et al.*, 2005; Lindell *et al.*, 2018).

At the same time a number of non-crop species can be alternative hosts for crop pests. The presence of alternative hosts is commonly considered to be a undesirable as they can be a source of pests that then attack crops. However, and especially for arthropod pests, alternative hosts can be advantageous as they not only host the pest but also the pest's natural enemies, i.e., the alternative host is acting as a 'banker plant' providing the **a**lternative prey / hosts of SN**A**P. Alternative hosts can also be used as early warning systems of potential pest outbreaks, by monitoring pest numbers out of crop season on the alternative hosts.

Unfortunately there is a dearth of research globally, and particularly in New Zealand vegetable growing systems as to whether alternative hosts are beneficial or not. As this effect will be specific to the species of both crop pest and the alternative host, and may well be impacted on other aspects of the agroecosystem, determining this for just a small proportion of vegetable pests and alternative hosts represents a huge amount of research. However, a key message is that just because a non-crop species is an alternative host does not mean that its presence can only be harmful, and that some alternative hosts could be beneficial.

This has been recently demonstrated in grapes where white clover (*Trifolium repens*) and hawksbeard (*Crepis capillaris*) have been found to be alternative hosts for longtailed mealybug (*Pseudococcus longispinus*) and citrophilus mealybug (*Pseudococcus calceolariae*). The alternative hosts are more attractive to mealybug than grapevines so they preferentially host on them. These mealybugs are then parasitised by the multiple species of mealybug parasitic wasps (parasitoids) that exist in New Zealand, which keeps mealybug populations below economic thresholds. Spraying out the alternative host plants in one vineyard resulted in the mealybugs moving into the vines at exceptionally high levels (Vaughn Bell, Rebecca Gough, Jonathan Hamlet, pers. comm. 2022).

Many vegetables are also highly susceptible to wind damage. Planting field margins in shelterbelts is an important wind mitigation tool. Thus there is considerable potential to maximise overall benefits by creating field margins and other non-crop areas that provide both wind protection and pest management.

3.3.1. Agroecological field margin plantings

A Lighter Touch is going to produce a separate report on field margin plantings for vegetable systems. Please see the a-lighter-touch.co.nz website for copies of the report when it is released. An alternative resource is the Foundation for Arable Research's (FAR) FAR Focus Issue 13 July 2018 'Biodiversity' far.org.nz/assets/files/blog/files//75f83a3f-b183-54b8-a9d2-714bfb4160bd.pdf

3.3.2. Minimising herbicides use in non-cropped areas to manage resistance

Herbicide resistance has been clearly demonstrated to be common across all New Zealand cropping systems with multiple weed species resistance to 1 (inhibition of ACCase), 2 (inhibition of ALS) and 9 (Inhibition of EPSP synthase (glyphosate)) modes of action (MoA) old A, B and G MoA. There are also a number of weed species, both grasses and broadleafs resistant to other modes of action. Herbicide resistance is therefore not a theoretical problem for the future but a real problem impacting farming and growing systems nationally.

A key driver of herbicide resistance is repeatedly using the same herbicide on the same area. It is common practice in New Zealand to use herbicides in non-cropped areas. For example, along road / track ways, the base of trees and the edges of grassed areas. Where non-cropped areas are repeatedly sprayed, especially with the same herbicide MoA, particularly glyphosate, there is a high likelihood of herbicide resistant weeds being selected. These could then be transferred to cropping paddocks where they may become a significant problem. New Zealand is also unusual in this non-cropping use of herbicides. In many European countries such uses are prohibited.

It is therefore vital to reassess the use of herbicides on non-cropped areas and find alternative management options. In many cases simply stopping spraying is the answer, with the added benefit of saving money and reducing climate impact through reducing diesel and herbicide use.

3.4. Rotations

The value of diverse rotations for pest management is well known, particularly soilborne arthropod pests and pathogens, as well as weeds and soil health (Merfield, 2019b). The downside of diverse rotations is the most profitable crops can only be grown more infrequently. A key enabler of reduced rotational diversity are the agrichemicals, which are direct replacements for the pest management benefits of rotations. Nitrogen fertilisers are the other direct rotational replacement, as these permit leguminous crops, particularly legume containing pasture, to be reduced or eliminated from the rotation.

With the need to reduce agrichemical use, due to issues such as evolved resistance, limited new chemical MoA, legislative and consumer pressure, and also pressure to reduce nitrate leaching and therefore nitrogen fertiliser use, use of more diverse rotations will be increasingly essential. Rotations also help with other aspects of agroecological and sustainable vegetable production, such as improving soil structure and which helps protect soil from erosion and improves crop performance.

3.5. Intercropping

Intercropping is the deliberate growing of two or more plant species together. It is being widely promoted overseas as an important agroecological technique to reduce agrichemical use and other benefits. It also covers a huge range of different approaches. For example, the intercropped plant species can be:

- All crops for sale (cash crops) e.g., lettuce intercropped with cabbages,
- One or more of the plants can be subsidiary (non-crop) plants, e.g., a white clover living mulch underneath cabbages,
- All subsidiary crops, e.g., a cover crop with multiple different species in it.

The scale at which the intercropping occurs also varies considerably, for example:

- Cultivar intercrops – different cultivars of the same species are mixed together,
- Intimate intercrops – the different species are mixed together at the individual plant level, e.g., lettuce plants alternating with cabbage plants, or a clover living mulch under courgettes,
- Crop rows – instead of a whole bed being planted with a single species different rows within the bed are planted with different species,
- Strip cropping – a bed, or group of beds, are alternated with different crop or non-crop species,
- Paddock / farm scale – agroforestry where widely spaced (e.g., 20 to 50 meters), low density woody vegetation are interspersed with vegetable production.

3.5.1. The ecology of intercropping

Intercropping primarily works by increasing plant diversity i.e., reducing monoculture. The ecological disadvantage of monoculture is that the plants are all susceptible to exactly the same pests. Especially for arthropod pests and pathogens there are few ecological barriers to stop their spread in a monoculture, as all the plants present are susceptible to attack, and are thus a vast food source for the pest to rapidly multiply upon. There are also few resources for beneficial species that can attack pests and limit their spread (such as SNAP see section 2.1) allowing pests free reign. Thus pests can quickly reach epidemic levels.

By intercropping different plant species, they act as a kind of pest 'fire break' for each other. The pests that attack one species can't attack other species in the intercrop so slowing, even halting their spread. For example intercropping is very effective at stopping the spread of potato late blight (*Phytophthora infestans*) (Ditzler *et al.*, 2021).

Intercrops also have indirect effects on pests, for example the different species can provide SNAP resources increasing the efficacy of beneficial organisms that can directly attack pests.

3.5.2. The challenges of intercropping

The obvious challenge of intercropping is that it adds complexity to the production system which in turn makes management more complex and potentially costly. Blocks of a single monoculture crop are easy to manage. Field operations, such as applying fertiliser, pesticides and harvesting can be done in one go across the whole block. Having different crops mixed in different rows in the same bed means such simple management systems would not be possible. A practical balance is thus needed between the most diversified systems which would be ecologically optimal and monocultures that are simplest for management. Strip cropping offers exactly the kind of balance between ecological complexity and management simplicity.

3.5.3. Strip cropping

Strip cropping where crops area grown in blocks of around five to twelve beds (6 to 12 meters width). Intensive market gardening in New Zealand often already has crops in small blocks so this is similar to some growers' current practices. However there is often no strategy as to which crops to grow next to each other. Research in the Netherlands (wur.nl/en/project/Strip-cropping.htm)[1] has found that there are good and bad combinations of crops to have in adjacent strips (Table 1).

Table 1. Strip cropping interactions (complied from page 17 of wur.nl/nl/show/redefining-the-field-towards-more-crop-diversity-dirk-van-apeldoorn-.htm (Apeldoorn, 2021)).
0 = neutral effect, - = negative effect, + = positive effect, / no data.

Crop	Bean	Broccoli	Celeriac	Oat	Onion	Parsnip	Potato
Bean	0	+	+	+	++	/	---
Broccoli	+	0	/	/	-	-	+
Celeriac	+	/	0	++	+	+	+
Oat	-	-	-	0	-	--	-
Onion	-	-	-	-	0	-	+
Parsnip	/	+	++	+	/	0	+
Potato	/	++	+	+	+	+	0

Not only are there specific pairs of neighbour crops that work well and those that do not, there is also a clear pattern that some crops are always good neighbours, including beans, celeriac, parsnip and potatoes, while others, including broccoli, oats and onions make poor neighbours (page 17, Apeldoorn, 2021).

3.5.3.1. Strip cropping and controlled traffic farming (CTF)

A further challenge of strip cropping is that crops have different sowing, harvesting etc., times, so that strips will need to be individually managed rather than the paddock as a whole. Keeping the beds and strips in the same location over time can be a challenge. Controlled traffic farming (CTF) is ideal for solving this challenge, while at the same time bringing considerable other benefits, such as reduced compaction and significant increases in yield. LandWISE has undertaken a range of CTF research in New Zealand field vegetables clearly showing substantial benefits, see landwise.org.nz/wp-content/uploads/Permanent-Beds-2013.pdf (Bloomer & Powrie, 2013).

3.5.3.2. Further information

Video "Strip cultivation in the experimental garden: the use of strip cultivation increases biodiversity in agriculture and prevents the spread of plant diseases" youtube.com/watch?v=Y52oOb-k9t0 in Dutch with English subtitles.

DiverIMPACTS - Diversification through Rotation, Intercropping, Multiple Cropping, Promoted with Actors and value-Chains towards Sustainability diverimpacts.net/toolbox.html

Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability plant-teams.org

ReMIX: Redesigning European cropping systems based on species MIXtures remix-intercrops.eu

[1] The Dutch version has more information wur.nl/nl/project/Strokenteelt.htm use the translation function in Google Chrome to translate the pages.

3.6. Subsidiary crop (cover crops)

Subsidiary cropping is a very large topic in and of itself. As per section 2.1 the terminology is somewhat confusing. 'Cover crops' along with 'non-cash crops' and 'subsidiary crops' are the over arching terms used, with subsidiary crop being the overarching term used in this report. Some research papers also use terms such as 'agroecological service crops', 'ecological service crops' 'ecosystem service crops'. These are not used outside the research literature, i.e., they are not common terms.

Subsidiary crops are the opposite of 'cash crops' which are grown for income / profit. Subsidiary crop are grown for indirect benefits to the farming system, such as soil health, nitrogen supply, nutrient mobilisation, reducing nutrient leaching and arthropod, pathogen and weed management. The main sub-forms of subsidiary crops include:

- Cover crops – a crop grown between cash crops to cover / protect the soil and ideally improve soil health,
- Smother crops – a crop grown in-between cash crops to smother out weeds and/or produce a large amount of biomass for mulch, e.g., for crimper roller systems (Merfield, 2007; Merfield, 2009),
- Green manures – a crop grown between cash crops for biological nitrogen fixation,
- Catch crops – a crop grown to reduce nutrient leaching, primarily nitrate,
- Living mulches – a crop grown underneath a cash crop to suppress weeds, fix nitrogen, conservation biocontrol, protect soil and improve soil health,
- Trap crops – a crop grown among or close to a cash crop to lure arthropod pests away from the cash crop and to trap them (see section 4.4),
- Biofumigation crops – very specific crop species and cultivars grown between cash crops that produce large amounts of biotoxic compounds that are incorporated into the soil to kill soilborne pests (see section 5.3).

Related to these types of subsidiary crops are the terms 'relay cropping' and 'undersowing' where the following cash or non-cash crop is sown into the first crop while the first crop is still growing. Relay cropping is where the second crop is sown close to harvest / end of the first crop. Undersowing is where the sowing of the second crop occurs not long after the first crop is established, or where the two are sown together.

Subsidiary crop will be covered in more detail the individual pest management sections.

3.6.1. Further information

Cover Crop Innovators Video Series. Sustainable Agriculture Research and Education (SARE) https://www.sare.org/What-We-Do/Impacts-from-the-Field/Cover-Crop-Innovators-Video-Series/

Cover crops a practical guide to soil and system improvement. 2015 NIAB TAG https://www.c-l-m.co.uk/wp-content/uploads/2017/07/NIAB-TAG-Cover-Crops-A4-guide-lo-res.pdf

Cover crops and soil health. USDA. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/climatechange/?cid=stelprdb1077238

Cover Crops for Sustainable Crop Rotations. 2015. Sustainable Agriculture Research and Education (SARE) https://www.sare.org/resources/cover-crops/

Cover crops. Wikipedia. https://en.wikipedia.org/wiki/Cover_crop

Green manuring principles and practice. 1927. Pieters. https://www.soilandhealth.org/wp-content/uploads/01aglibrary/010160.Pieters.pdf

Links to multiple cover crop resources. SoilCare. https://www.soilcare-project.eu/soil-improving-cropping-systems/soil-improving-crops/20-cropping-systems/142-cover-crops

Managing Cover Crops Profitably, 3rd Edition. 2007. Sustainable Agriculture Research and Education (SARE) https://www.sare.org/resources/managing-cover-crops-profitably-3rd-edition/

OSCAR (optimising subsidiary crop applications in rotations)) https://web5.wzw.tum.de/oscar/wiki/index.php/Main_Page (note the website owners keep changing the number in their domain i.e., web5.wzw.tum.de so if the above link breaks then please try larger numbers e.g., web6, web7, web8 until one works

OSCAR: a collaborative European research project to develop more sustainable systems of conservation agriculture and increase the diversity of cover crops and living mulches. https://web5.wzw.tum.de/oscar/wiki/index.php/Main_Page

SARE. Cover Crops Webinars. 2012. Sustainable Agriculture Research and Education (SARE) https://northcentral.sare.org/resources/sare-cover-crops-webinars/

Short duration cover crops for vegetable production systems. 2016. Iowa State University https://mccc.msu.edu/wp-content/uploads/2016/09/IA_2016_Short-Duration-Cover-Crops-for-Vegetable-Production-Systems.pdf

Short-term green manures for intensively cultivated horticultural soils. 2018. AHDB. https://projectblue.blob.core.windows.net/media/Default/Imported%20Publication%20Docs/Green-manures-for-intensively-cultivated-horticultural-soils.pdf

Sort out your soil - A practical guide to green manures. 2011. Rayns Rosenfeld https://www.cotswoldseeds.com/articles/291/sort-out-your-soil-practical-guide-to-green-manures

North Eastern Cover Crops Council decision tool https://northeastcovercrops.com/decision-tool/

3.7. Biopesticides

Biopesticides are direct biological substitutes for the agrichemical pesticides, in that they are a purchased, manufactured product with a biological origin that is typically applied with an agrichemical sprayer or similar equipment. They can directly kill the pest as well as damage and repel them. They range from whole living organisms through to purified extracts. Most originate from bacteria, fungi and other microorganisms, as well as other species such as nematodes and plants.

Biopesticides are a type of inundative augmentative biocontrol, see section 4.3. They are covered in detail in the report "Literature review: Enhancing agroecosystems for augmentative biological control" (Bellamy *et al.*, 2020) written for A Lighter Touch by Plant & Food Research. They therefore will not be covered in this report. To get a copy of the report please email news@a-lighter-touch.co.nz giving the title of the report and asking for a copy.

4. Arthropod pest management

The main physical management for arthropod and vertebrate pests in vegetables are mesh crop covers. Examples of other physical techniques include traps, such as yellow sticky traps and vacuuming up insects or blowing them off crops with compressed air, for example in potatoes (Boiteau *et al.*, 1992). The main biological / ecological arthropod pest management approach is biocontrol in the broad meaning. This is likely to be mostly based around conservation biocontrol, but, not exclusively.

4.1. Mesh crop covers for arthropod and vertebrate pests

Mesh crop covers are a highly effective arthropod and vertebrate pest management tool (Merfield, 2017b). They are widely used in Europe and Israel where they were first used in the early 1990s, and are being increasingly used in an increasing range of countries, including New Zealand.

Conceptually they are like fly screen for crops. They are a physical barrier that stops pests reaching the crop, thus achieving close to 100% control with exceptional reliability. They are used in the same way as frost cloth like Mikroclima and Agryl®, being laid directly on top of the crop. Unlike frost cloth they are designed to minimise the amount of heat they trap and maximise air-flow, so they can be used year-round, even in the middle of summer.

Mesh crop covers can be used on a practically all field vegetable crops. Exceptions are where abrasion of the top most leaves may result in failing market specifications, e.g., for baby salad leaves. This issue can be overcome by using supports, such as cloche hoops, to keep the mesh off the crop. Or for very tall crops, e.g., sweetcorn, where covering such a tall crop with mesh crop covers my be impractical.

Apart from these small limitations, mesh crop covers can control nearly all arthropod and vertebrate pests on nearly every vegetable crop. As they are a physical barrier, they stop pests reaching the crop so minimise all forms of damage. This is particularly valuable for arthropod pests that transmit viruses and pathogens (such as aphids and tomato potato psyllid (TPP, *Bactericera cockerelli*) as mesh crop covers prevent transmission. They will also likely control new pest threats, such as brown marmorated stink bug (*Halyomorpha halys*). If a vegetable production system is already geared up to use mesh, when new pests arrive it is highly likely that mesh crop covers will highly effectively control them. The same cannot be said of agrichemical pesticides, as products will need to be tested and approved potentially leaving several years were management with agrichemicals will not be possible or is limited in effectiveness, as happened for TPP in potatoes. Mesh therefore is valuable insurance that will allow production to continue without interruption when the next biosecurity breach occurs.

Mesh crop covers also provide exceptional levels of reliability, in that if they are visibly in place on the crop they can be guaranteed to be working, unlike agrichemicals. For many crops they also improve the crop microclimate, which can directly increase marketable yield.

They have also been extensively proven on farm over three decades, with all the supporting infrastructure, such as handling machinery, easily available. See Merfield (2017b) bhu.org.nz/future-farming-centre/ffc/information/crop-management/production/mesh-potatoes/mesh-crop-covers-for-pest-control-in-commercial-crop-production-2017-ffc-merfield.pdf for a detailed explanation of commercial use of mesh crop covers.

For example, research in New Zealand on controlling TPP on potatoes comparing an intensive agrichemical regime (both insecticides and fungicides) and mesh crop covers achieved an average of less than one TPP under mesh crop covers compared with over 400 TPP in the agrichemical treatment. This produced a 24% increase in marketable yield for the mesh over agrichemicals resulting in an increase in profit of up to 75% by using mesh (Merfield, 2017a). Mesh crop covers have also been shown to reduce the incidence of potato blight (Merfield, 2012, 2013) so the effect of mesh on disease pressure can be positive, i.e., it should not be assumed that mesh crop covers will make crop pathogens worse.

Mesh crop covers are thus considered a key ‘drop-in’ technology to directly replace agrichemical management of arthropods and vertebrate pests on a wide range of field vegetables, while potentially increasing marketable yield and profitability.

4.2. Biocontrol of arthropod pests

As discussed in section 3.1 there are three sub-types of biocontrol, introductory, augmentation and conservation. Introductory biocontrol is outside the control of individual growers, although they clearly can benefit from introduced BCAs, so introductory biocontrol is not covered in this report

Inundation augmentation, principally in the form of biopesticides is considered to have considerable potential to directly replace agrichemical pesticides in vegetables. Inoculative augmentation, e.g. purchasing BCA from commercial suppliers, is considered to have some potential.

Conservation is viewed has having the biggest potential in vegetable production, as while growers need to undertake some of the development work themselves, a well designed conservation biocontrol system, that is created to include wider agroecological benefits, such as soil protection, nitrogen supply, general biodiversity, and system robustness and resilience, will have multiple benefits, often at low ongoing management costs.

4.3. Augmentation biocontrol

Inundative augmentative biocontrol for vegetables in New Zealand is mainly in the form of biopesticides. These are covered in the report “Literature review: Enhancing agroecosystems for augmentative biological control” (Bellamy *et al.*, 2020) written for A Lighter Touch by Plant & Food Research. Please see section 3.7 for information on how to get a copy of the report.

Introductory augmentative biocontrols are available from a number of companies supplying BCAs to the glasshouse and protective cropping industries. While their use is routine in glasshouses, their use in field vegetables is limited, mainly due to the open nature of field veg compared with closed glasshouse systems which contain the beneficials on the crop and the economics of using them in field veg where the returns per ha are much lower than protected cropping. Their use in field vegetables is therefore likely to be limited, but, there may be specific situations (crop × pest combination) where they are a valuable tool.

4.4. Conservation biocontrol

The main approach to biocontrol of arthropod pests in vegetable production systems is thus considered to be conservation biocontrol. It is also the most agroecological of the biocontrol approaches and therefore best aligns with A Lighter Touch and this project. It also puts growers in the driving seat in having the greatest control over its implementation, its costs and benefits. However, it is least the explored and researched form of biocontrol in vegetable production. There is fortunately a significant ramping up of overseas research, particularly in Europe that can be leveraged in New Zealand.

4.4.1. Agroecological field margin plantings

A Lighter Touch is going to produce a separate report on field margin plantings for vegetable systems. Please see the a-lighter-touch.co.nz website for copies of the report when it is released. An alternative resource is the Foundation for Arable Research’s (FAR) FAR Focus Issue 13 July 2018 ‘Biodiversity’ far.org.nz/assets/files/blog/files//75f83a3f-b183-54b8-a9d2-714bfb4160bd.pdf

4.4.2. Targeted vs. broad brush conservation biocontrol

As discussed in section 3.1.3.1 conservation biocontrol can be undertaken in a targeted approach, addressing individual pest and crop combinations, or in a broader brush approach that targets a large number of pests in one go.

Despite the large diversity of arthropod pests and the crops they attack, the natural enemies species that occur in the conservation biocontrol literature is very small, considering the vast diversity of arthropods. These include ladybirds (Coccinellidae) hoverflies (syrphid flies, Syrphidae), lacewings (Neuroptera), parasitoids (mostly in the Hymenoptera), carabid (ground) beetles (Carabidae), rove beetles (Staphylinoidea), predatory mites (Arachnida), spiders (Araneae), harvestmen (Opiliones) and true bugs e.g., pirate bugs, assassin bugs (Heteroptera) (Hopwood *et al.*, 2016). Some of these natural enemies are generalists, i.e., they attack a wide range of arthropod pests, and others specialists i.e., where one natural enemy attacks one pest species or a few closely related pest species (e.g., closely related aphid species).

The desk study undertaken for the ALT project 'Demonstrating agroecological and conservation biocontrol of arthropod pests in perennial cropping systems' (Merfield & Shields, 2021) found that despite the wide evolutionary variation in the BCAs the conservation biocontrol modifications and SNAP plants listed in the literature that promoted the BCAs came down to a relatively small list of common plant species. These included annual and perennial grasses, legumes (mostly clovers), and annual and perennial forbs such as alyssum (*Lobularia maritima*), dandelion (*Taraxacum officinale*), fennel (*Foeniculum vulgare*), buckwheat (*Fagopyrum esculentum*), phacelia (*Phacelia tanacetifolia*) and marigolds (*Tagetes*).

Merfield & Shields (2021) suggested that due to scientists having a tendency to copy methods from previous research, it may mean that the same small range of plants is repeatedly chosen to test for their conservation biocontrol potential, thus the same plants keep getting selected. Rizvi et al. (2022) also noted the small range of plants identified in their review. However, in addition to its ability to support natural enemies, for a plant to be viable as an arthropod conservation biocontrol species, there are a considerable number of additional selection criteria. For example, the plants / seeds need to be commonly available, not too expensive, the plants are easy to grow and manage, the right size, they are not weeds / pests themselves, etc. This means that the range of plants to choose from is actually quite narrow. It may also be that some plant species are particularly effective, for example Prof. Steve Wratten consistently found that either phacelia (*Phacelia tanacetifolia*), buckwheat (*Fagopyrum esculentum*) or alyssum (*Lobularia maritima*, syn. *Alyssum maritimum*) were the best nectar and pollen sources (S. Wratten, pers. comm.). It is therefore suggested that the exact species chosen for more general conservation biocontrol is probably less critical than having a diverse range of species from the literature, that will therefore support the biggest range of natural enemies. Thus increasing the overall diversity of vegetable production systems, both within crop and non-crop areas, has good potential to boost natural enemies and suppress arthropod pests.

As arthropod pests can invade crops in large numbers and/or rapidly build up their populations (e.g., aphids) having a sufficiently large populations of BCAs year round - a 'standing army') - that can attack crop pests as they appear is considered vital. Therefore permanant plantings, both within and around paddocks to maintain a background population of BCAs are required. Shorter term annuals may still have an important role to play in specific crops.

4.4.3. SNAP

One of the main sub-components of conservation biocontrol is the SNAP concept promoted by Prof. Steve Wratten of Lincoln University (Barnes *et al.*, 2009; Gurr *et al.*, 2017; González-Chang *et al.*, 2019). SNAP stands for **S**helter, **N**ectar, **A**lternative prey / hosts and **P**ollen . These are key ecological resources that beneficial arthropods require to boost their populations and fecundity (number of eggs / young produced) to bring pests below economic thresholds.

SNAP is sometimes referred to as 'floral resources', however, this term does not encompass shelter or alternative prey / hosts, which are as if, if not more, important than flowers. 'Floral resources' also tends to make people focus on the larger showy, broadleaf flowers, ignoring the pollen from grasses. Grass pollen often feeds a quite different set of beneficial arthropods, e.g., mites, as it is much smaller because it is wind-blown. This report therefore will refer to nectar and pollen rather than floral resources.

Also just focusing in on nectar and pollen underestimates the importance of shelter and alternative prey / hosts. Shelter, in terms of habitat for beneficials is vital, and typically required year round. This includes shelter:

- For beneficials to rest in when inactive,
- From adverse weather,
- From their own enemies, e.g., birds and other arthropods,
- During winter when they are hibernating,
- Etc.

Individual beneficial species may therefore require multiple types of shelter, both in space and time.

Many beneficial species are specialists – i.e., they only feed, prey, attack and parasitise a single or small group of host / prey species. If these prey / hosts are only present for part of the year, e.g., when the host crop is present, then the beneficials can only be present when the prey / hosts are around. They will then be slow to return and build up their populations when the host crop is planted again and the pests return. By creating habitat that allows the pest to be present all year round then there is year round prey / hosts for the beneficials, thus maintaining sufficient populations to attack pests in the cash crops.

The use of alternative prey / hosts also applies to generalists. The key difference and advantage is that non-pest species can be promoted as the alternative prey / host so there is no risk to the crop.

One example of habitat manipulation to support alternative prey / hosts are 'banker plants' or 'banker crops'. These are subsidiary crops planted to deliberately host prey / hosts of beneficials. These can be both the arthropod pest of the crop itself, or, species that don't host on the crop. If the banker plant hosts crop pests they it can also be described as 'alternative host' plants. These are typically considered bad and unwanted as they perpetuate the pest in the cropping system including acting as a green-bridge (non-crop plants that provide a 'bridge' of living green foliage when crop foliage is not present, e.g., over winter). However, from an ecological view, maintaining a population of pests in the production system which allows their predators to also maintain their populations is a viable way of stopping the pests breaching economic thresholds by supporting their natural enemies.

See section 3.1.3 for the example of the importance of alternative hosts for mealybug management in vineyards.

4.4.4. Non-SNAP approaches

There are a number of biocontrol approaches that fall outside of SNAP but are still part of conservation biocontrol.

4.4.5. Trap crops

'Trap crops' are subsidiary crops that are more attractive to the pest than the cash crop, so the pest is attracted out of the cash crop and into the trap crop. In the best case, the trap crop is a 'dead-end' for the pest because they lay eggs or otherwise produce offspring on the trap crop, but, the offspring cannot survive on the trap crop and die. In other cases the pest can be managed while on the trap crop. Options include:

- Physical destruction of the trap crop and the pests on it. For example, flail mowing and / or ploughing under. This can be used against both adults and juveniles.
- Agrichemicals. As the trap crop is not a food crop, the range of agrichemicals that can be used against the pest is wider, and can include chemicals that are prohibited on food crops. This allows for better rotation of agrichemical modes of action, to help manage pest resistance.

4.4.6. Intercropping

Intercropping is where different species of plants, both cash and subsidiary crops are grown together, with the mixing taking place at a range of scales from plant to paddock level, see section 3.5 for more details. This can be a highly effective means of managing arthropod pests.

4.4.7. Push-pull

Push-pull is where an attractant - the 'pull' and repellent – the 'push' strategy are used together. This typically involves the use of a trap crop as the pull and an intercrop as the push. The most famous example of this is the management of stemborer caterpillars and the parasitic witchweed (*Striga* spp.) in maize in Africa (wikifarmer.com/the-push-pull-strategy-controls-stemborers-and-striga-increasing-corn-yields). Napier grass (*Pennisetum purpureum*) is planted around the outside of the maize plots as a trap crop. It is the pull, as it is more attractive to the adult stemborer moths than the maize. It is also a dead-end trap crop for the stemborer caterpillars because the Napier grass produces a gum when the caterpillars bore into it trapping and killing them. Silverleaf (*Desmodium uncinatum*) is planted as an intercrop among the maize plants. This produces chemicals that repel the adult moths, pushing them out of the maize. It also produces chemicals from its roots that prevent the striga seedlings attaching to the maize roots. This makes the striga seed germination suicidal as without attaching to the maize roots the seedlings die. Silverleaf is also a legume so it fixes nitrogen, which is transferred to the maize via mycorrhizae fungi. This is all achieved without the farmers having to purchase any inputs, particularly pesticides the use of which is not without issue in Africa and other developing countries. The farmers save the seeds from the maize, Napier grass and silverleaf to plant for the following year, making the system completely self-sufficient. The push-pull system has thus been utterly revolutionary for maize production in Africa.

4.4.8. Vegetables conservation biocontrol research

Below are listed a number of studies of conservation biocontrol in a range of vegetable crops as examples of approaches that can be tried as part of this project.

4.4.8.1. Single vs. multiple techniques

Most studies only use a single technique, but, in real-world production there are good reasons why multiple techniques should be used. There may be both synergies and antagonism when techniques are combined, so, where combined techniques are used they should also be thoroughly tested before being used at commercial scales.

4.4.8.2. Limitations of scale – extrapolating plot studies to field-scale

A key limitation of many studies is that they were undertaken in small research plots, rather than in real-world, field-scale situations. Both arthropod pests and beneficial insects are mobile, and can move many tens even hundreds of meters in a day. Multiple studies show that how the cash and subsidiary crops are spatially arranged has a large impact on effectiveness. For example, subsidiary crops range from being intimately mixed with crop plants, to being placed around the edge of research plots and fields. The distance between the cash and subsidiary crops therefore ranged from a few centimetres to hundreds of meters. Extrapolating from plot scale studies to field-level effects is therefore simply not possible. To determine field-scale efficacy, research has to be conducted at field scale.

4.4.8.3. Where has the yield gone?

Another issue with many studies is they do not measure yield, especially marketable yield, which means they are completely lacking evidence if the technique is commercially valid and maintain or better increase profit. Many instead measure variable such as numbers of beneficials, reduction in pest numbers, and even more detailed scientific measurements. While such information is valuable to inform future scientific work, it, is of limited value for commercial production, because there is rarely a simple relationship between increased beneficials, decreased pests, increased marketable yield, costs and thus profit. The only way to determine if any of these techniques are going to be both effective and economically viable is to test them at field-scale, at multiple locations and years on real-world vegetable farms.

4.4.8.4. Inherent variability of conservation biocontrol

Conservation biocontrol is inherently variable as it is based on variable ecosystem processes. To demonstrate viability in commercial vegetable systems, research needs to be conducted across multiple sites and multiple years. Three sites and three years, giving nine independent experiments, is considered the minimum to give the results a sufficient level of certainty to be implemented in commercial production with low risk of unexpected outcomes. Five sites and five years (25 independent experiments) is considered to give robust level of certainty. Very few research papers have undertaken this level of research replication.

4.4.8.5. Research examples

The following are short summaries of conservation biocontrol from the literature. They have been selected based on factors including: relevance to New Zealand vegetable production, include measures of yield (particularly where yield increases) and/or demonstrate an interesting approach. The aim is to highlight a diverse range of approaches across a number of vegetable crops, rather than provide explicit examples that can be directly implemented in the demonstration sites associated with this project. Where there is a desire to trial / demonstrate a particular approach as part of this project then the specific approach should be researched in more detail, e.g., find further examples in the literature.

It should be noted that some organisms described in the research are not present in New Zealand (see also 2.6), but they have been included as the conservation biocontrol approach itself is worthwhile trialling in New Zealand.

Please see section 2.6 around issues of the applicability of overseas research.

In Minnesota, USA, buckwheat (*Fagopyrum esculentum*) planted around 12 × 20 m plots providing nectar and pollen improved parasitism of lepidopteran cabbage pests over four years (Lee & Heimpel, 2005).

In Adelaide, Australia, alyssum (*Lobularia maritima*) and pak choi (*Brassica campestris*) were planted to provide nectar to parasitoids that host on the diamondback moth (*Plutella xylostella*). The alyssum and pac choi were planted down the middle of beds of broccoli. While the flowering plants did increase numbers of parasitised caterpillars the difference was not statistically significant (Keller & Baker, 2002). In comparison in New Zealand buckwheat did increase parasitism of diamondback moth by *Diadegma semiclausum* (Lavandero *et al.*, 2005).

In Switzerland, cornflower (*Centaurea cynanus*) interplanted in 3 × 9 m cabbage plots increased parasitism of lepidopteran caterpillars (Balmer *et al.*, 2013).

In Australia, buckwheat reduced crop damage by the caterpillars of *Helicoverpa* spp. on sweetcorn grown in plots consisting of 12 corn plants in a row with buckwheat intercropped among the corn plants (Simpson *et al.*, 2011).

In a field scale study in Belgium using 125 × 8 m wildflower strips increased the populations of parasitoids of pollen beetles (*Meligethes* spp.) and true weevils (*Ceutorhynchus* spp.). Wildflower species included *Aethusa cynapium*, *Anthriscus sylvestris*, *Heracleum sphondylium*, *Achillea millefolium*, *Crepis biennis*, *Hypochaeris radicata*, *Leontodon hispidus*, *Leucanthemum vulgare*, *Matricaria recutita*, *Capsella bursa-pastoris*, *Sinapis alba*, *Knautia arvensis*, *Lotus corniculatus*, *Medicago lupulina*, *Trifolium pratense*, *Trifolium repens*, *Geranium pyrenaicum*, *Origanum vulgare*, *Prunella vulgaris*, *Lythrum salicaria*, *Malva moschata*, *Galium verum*, *Agrostis capillaris*, *Festuca rubra*, *Poa pratensis* (Hatt *et al.*, 2018).

In Hawaii intercropping cabbages and tomatoes at the plant level increased the level of parasitism of diamondback moth by *Cotesia plutellae* compared with plots of monocropped cabbage (Bach & Tabashnik, 1990). Also in Hawaii, intercropping broccoli with yellow sweet clover (*Melilotus officinalis*) reduced numbers of early instar cabbageworm (*Artogeia rapae*) compared with broccoli monoculture but late instar cabbageworm numbers were significantly higher in intercropped broccoli during the rest of the season. In contrast Cabbage looper (*Trichoplusia ni*) was consistently lower in the intercropped broccoli (Hooks & Johnson, 2002).

Intercropping can dramatically reduce pest damage not only by increasing natural enemies, it can also reduce pest damage due to increasing the number of 'inappropriate landings' of the pest on the intercrop (Finch & Collier, 2000, 2003). Figure 3 shows the reduction of eggs laid by eight cabbage insect pests growing in clover living mulch.

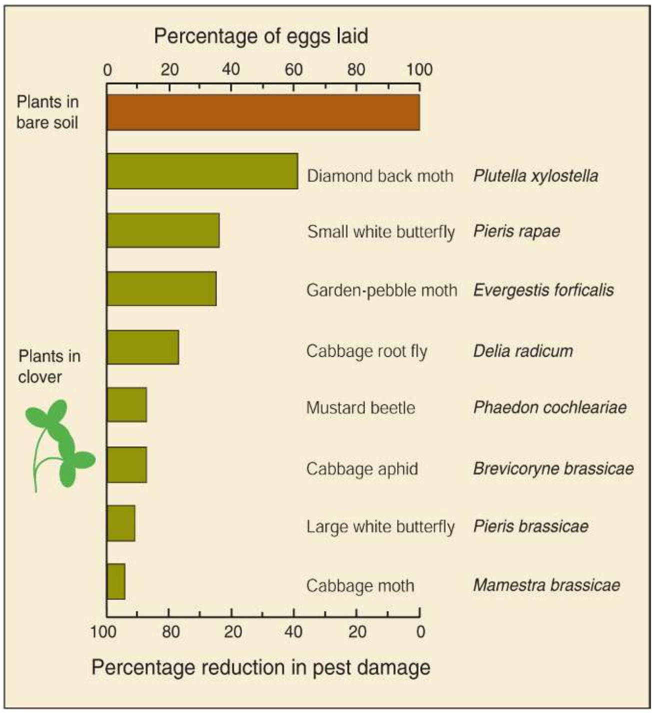

Figure 3. Numbers of eggs laid by eight insects on cabbage plants growing in clover (green columns) expressed as percentage of eggs laid on similar plants growing in bare soil (top brown column). From (Finch & Collier, 2003).

In Ghana, intercropping cabbage with either tomato, pepper or onion in 1.35 × 1.80 m plots was found to be as effective as spraying the cabbage with chlorpyrifos (Dursban) (Asare-Bediako *et al.*, 2010).

In Sweden, planting a trap crop of Indian mustard (*Brassica juncea*), around 6 m^2 plots of white cabbage resulted in diamondback moths laying approximately half the number of eggs on the cabbages compared with cabbages without the mustard trap crop (Åsman, 2002). Moth larvae survival was also lower on the mustard.

In Florida, USA, planting kale (*Brassica oleracea*) borders around cabbage fields over two years resulted in significantly less diamondback moth eggs on cabbage. Diamond back moth numbers never exceeded the IPM action threshold for insecticides application in any of the fields that were completely surrounded by kale, but did exceed the action threshold in three of the fields without collards on four sampling dates in one year (Mitchell *et al.*, 2001).

In Hawaii, using 14 × 14 m plots of sweetcorn interplanted in rows with buckwheat (*Fagopyrum esculentum*), cowpea (*Vigna unguiculata*) and sunn hemp (*Crotolaria juncea*) increase the parasitism of corn earworm (*Helicoverpa zea*) eggs by *Trichogramma* spp. and predation by *Orius* spp. by the buckwheat providing nectar and pollen and the cowpea and sunn hemp providing alternative hosts for *Trichogramma* spp. (Manandhar & Wright, 2015).

In Kenya intercropping French beans with sunflower, potato, or baby corn in 5 × 10 m plots reduced the number of four species of thrips on beans coupled with an increase in the natural enemies *Orius* spp. and *Ceranisus* spp. particularly in the baby corn intercrop (Nyasani *et al.*, 2012).

In a two year study in Spain, coriander (*Coriandrum sativum*) or *Glebionis coronaria* (syn. *chrysanthemum coronarium*) were trialled as nectar and pollen sources for hoverflies (Syrphidae) to attack the aphid *Nasonovia ribisnigri* in lettuce. Plots were 10 m long with ten rows of lettuce, with the coriander and *Glebionis coronaria* planted on the outside of the plots. Contrary to expectations lettuces with coriander intercrop had higher aphid populations than the lettuce monoculture control (Pascual-Villalobos *et al.*, 2006).

In Poland, carrot was intercropped with coriander (*Coriandrum sativum*) or summer savory (*Satureja hortensis*) in 2.10 × 4 m plots in rows 35 cm apart with the intercrops planted in the outside rows over two years. The populations of the willow carrot aphid (*Cavariella aegopodii*), waxy carrot aphid (*Semiaphis dauci*) and the bean aphid (*Aphis fabae*) were 50% higher in the carrot monoculture than intercrops. There was a reduction in carrot root fly (*Psila rosae*) root infestation of 67% for coriander and 80% for summer savory. Ladybirds (Coccinellidae) and hoverfly (Syrphidae) populations were greater in the intercropped carrots than the monoculture (Jankowska & Wojciechowicz-Żytko, 2016).

In a related study, also undertaken in Poland over two years, carrot was intercropped with French marigold (*Tagetes patula nana*) or common marigold (*Calendula officinalis*) in 10 m^2 plots on 68 cm wide rows with the intercrops planted between the carrot rows. The results varied between years, with marketable yield doubling in the first year but being the same in the second year. Intercropping reduced carrot root fly (*Psila rosae*) root infestations by 61% for French marigold and 35% for common marigold. Roots infested by nematodes (species not given) reduced by 55% for French marigold and by 90% for common marigold. Carrot psyllid (*Trioza viridula*) showed similar large reductions (Jankowska *et al.*, 2012).

Intercropping carrots with onions in the United Kingdom reduced carrot root fly (*Psila rosae*) damage on carrots and onion thrips (*Thrips tabaci*) on onions compared monocultures. The treatment effect was greatest when the carrots were intercropped with young onions but virtually ineffective once the onions began to bulb (Uvah & Coaker, 1984).

Over four years in the Netherlands, in commercial vegetable fields with high carrot root fly (*Psila rosae*) population, undersowing carrots with subterranean clover (*Trifolium subterraneum*) increased marketable yield of carrots by 60% and reduced root fly damage by 75% averaged over the four years. There was also a 73% reduction in cavity spot (*Pythium* spp.) in the intercropped carrots over the four years (Theunissen & Schelling, 2000).

In Sweden at three sites on organic farms, more mature carrots were used as a trap crop for the carrot psyllid, (*Trioza apicalis*). The mature carrots were planted around the edge of the field, which concentrated egg laying on the field edges, which were then destroyed by cultivation (Cotes *et al.*, 2018).

In Egypt over two years, in 8.4 m^2 plots, Faba bean (*Vicia faba*) was intercropped with fenugreek (*Trigonella foenum-graceum*), coriander (*Coriandrum sativum*) or onion (*Allium ceba*) to manage the black legume aphid (*Aphis craccivora*). Both coriander and fenugreek reduced aphid populations with fenugreek nearly halving aphid numbers. Onion only slightly reduced aphids in one year. Fenugreek also increased yields up to 33% (Abdullah & Fouad, 2016).

In Kenya, over three plantings using 3 × 10 m plots with two 50 cm wide rows of French bean (*Phaseolus vulgaris*) was intercropped with a row of Aztec marigold (*Tagetes erecta*), carrot (*Daucus carota*), coriander (*Coriandrum sativum*), kale (*Brassica oleraceae* var. *acephala*), capsicum (*Capsicum annuum*), or maize (*Zea mays*). Kale and capsicum had no effect on trip numbers, carrot reduced thrips moderately, while maize, coriander and marigold reduced thrips more effectively than methiocarb (Kasina *et al.*, 2006).

Idris & Grafius (1996) found that winter cress / yellow rocket (*Barbarea vulgaris*) is a dead-end trap crop for diamondback moth (*Plutella xylostella*).

Rosemary (*Rosmarinus officinialis*) has been shown in laboratory based studies to be repellent to both male and female western flower thrips (*Frankliniella occidentalis*), flower thrips (*Frankliniella intonsa*) and melon thrips (*Thrips palmi*). The presence of rosemary plants significantly reduced settlement of females of all three thrips species and eggs laid by western flower thrips. It was suggested that a rosemary extract could be used as part of a push-pull strategy (Li *et al.*, 2020). Rosemary extracts may therefore be part of a push-pull system to control onion thrips (*Thrips tabaci*).

5. Pathogen management

Agroecological management of plant pathogens (diseases) is mostly based on prevention than cure, as, once a pathogen is present in a crop at problematic levels the ability to suppress / cure it is more limited. Agroecological management of plant pathogens also contrasts strongly with conservation biocontrol of arthropod pests. There is no equivalency between the broad-brush, on-farm habitat diversification, which boosts the natural enemies of crop arthropod pests, and equivalent diversification of on-farm habitat for pathogen management. The ecology of the arthropod pests and plant pathogens are completely different. Therefore quite different approaches are required. This contrasts strongly with agrichemical management: both arthropod pests and pathogens are managed through agrichemicals applied by a sprayer. This similarity in agrichemical management hides the vastly different agroecological approaches that are required. The main exception to this, and, nearly the only biological / ecological approach that can cure existing pathogen outbreaks are the biopesticides.

5.1. Biopesticides

The big advantage of biopesticides are they are often a straight drop-in replacement for agrichemical pesticides (see section 3.7). They are both applied using standard spraying technology and they work in the same way, i.e., both preventably and curatively (depending on the individual product). They can also be as, or even more, effective than chemical equivalents (O'Brien, 2017).

Biopesticides are also a type of inundative augmentative biocontrol (see section 4.3). The biopesticides that are available in New Zealand are covered in detail in the report "Literature review: Enhancing agroecosystems for augmentative biological control" (Bellamy *et al.*, 2020) written for A Lighter Touch by Plant & Food Research. . They are therefore so are not covered any further in this report. See section 3.7 for information on how to get a copy of the report.

5.2. Biostimulants

There continues to be a growing interest in biostimulants, both in New Zealand and overseas. Despite the interest there are few formal definitions. One is from the 2018 Farm Bill in the USA.

> "A biostimulant is a substance or microorganism that, when applied to seeds, plants, or on the rhizosphere, stimulates natural processes to enhance or benefit nutrient uptake, nutrient use efficiency, tolerance to abiotic stress, or crop quality and yield." [2]

Thus the key difference between a biostimulant and a fertiliser (mineral or organic) is biostimulants contain only small, even tiny, amounts of nutrients (i.e., the essential plant elements) (Merfield & Johnson, 2016). Their effects are entirely dependent on manipulating plant mutualists, plant biology, and plant biochemistry.

Biostimulants are also currently unregulated in New Zealand (and many other countries). It is therefore something of a 'wild west' and the warning of caveat emptor strongly applies. There are many products that work as described which are based on a significant amount of peer-reviewed scientific research. There are also products where the mode of action is opaque and no science to back up claims is available. There are also nearly as many modes of action as their are products, and the number numbers of companies and range of products continues to grow rapidly. It is thus impossible to make a general statement if biostimulants work or not. The evaluation has to be at the level of individual product and its specific purpose. Independent expert advice is strongly recommended, coupled with the existence of peer-reviewed science that underpins a particular product.

[2] ag.umass.edu/greenhouse-floriculture/fact-sheets/what-are-biostimulants

Despite these challenges, as for biopesticides, biostimulants are considered to have considerable potential for pathogen management in vegetables and further work should be undertaken to identify specific products that could provide or assist with pest management.

5.2.1. Biological seed treatments

The use of living microbial biological seed treatments, e.g., bacteria and fungi, is considered to have particular potential. Treating seed means that beneficial organisms are inoculated onto the plant from germination, which is particularly important for root associated beneficials. Due to the small size of most vegetable seeds, only small amounts of inoculum are required to treat a large number of seeds, so it is highly cost effective, even when the product is expensive. Seeds can also be treated and then quickly planted to maximise the beneficials viability. A number of microbes originate in soil so quickly die or loose efficacy when applied to plant foliage.

Regenerative farmers in New Zealand and overseas are reporting considerable successes with biological seed treatments to replace chemical seed treatments. It would be worth testing the products they are using on vegetable seeds and comparing those with untreated and chemically treated seeds.

5.3. Rotations

As discussed in section 3.4, rotations are a highly effective tool, particularly again soilborne pests especially pathogens.

5.3.1. Research example

One example of the benefits of rotations in New Zealand vegetable production systems looked at the impacts of increased crop yield of potatoes and onions were grown in diversified rotations where they were each grown one year in four, compared with more intensive alternating potato-onion rotations or continual monoculture cropping (Wright *et al.*, 2017). Marketable yield for potatoes from the monoculture was 48.5 t/ha compared with the four year rotation 82.1 t/ha a 69% increase. For onions the monoculture yielded 32.31 t/ha the rotation 57.38 t/ha a 78% increase (Wright *et al.*, 2014). This clearly shows the agronomic and economic value of rotations, and as practical and scientific benefits of rotations are well known, and there is low risk of negative effects, increasing rotational diversity should be a key technique New Zealand vegetable growers can implement to reduce both pests and agrichemical use.

5.3.2. Further information

Crop rotation on organic farms: A planning manual sare.org/resources/crop-rotation-on-organic-farms/ (Mohler & Johnson, 2009). While this book is titled 'on organic farms' the material is just as applicable to non-organic farms as well.

5.4. Irrigation

Many plant pathogen, especially fungi, are strongly effected by water, e.g., soil moisture, atmospheric relative humidity, leaf wetness, etc. While rain and humidity are out of the growers control, irrigation is. Traditionally in vegetables irrigation has been applied overhead, e.g., with sprinklers. The potential for managing foliar pathogens by switching to surface or subsurface irrigation is considered to have good potential and could be explored as part of this project.

5.5. Solarisation and biofumigation

Where soilborne pests have built up to high levels, soil solarisation and biofumigation are alternatives for agrichemical fumigation and steam pasteurisation. However, if soilborne pests have reached such levels that curative action is required, it clearly indicates there are system level issues, such as lack of rotation (see section 3.4) that need to be fixed, so the problem is not recreated in future.

5.5.1. Solarisation

Solarisation uses very thin clear plastic, laid on bare moist soil, in the middle of summer for about six weeks. Just like a glasshouse, the plastic traps the sunlight's energy to heat the soil. Soil temperatures need to reach at least 40°C and ideally 60°C. It is both the temperature and the duration of treatment that kill the pests. The use of very thin clear plastic, bare soil that is moist during the whole treatment duration are critical for good efficacy.

5.5.2. Biofumigation

Biofumigation works by shredding and thoroughly mixing into the soil, specific species of subsidiary crops that produce very high concentrations of biotoxic gasses. A quickly as possible after incorporation, the soil surface is sealed to minimise the loss of biotoxic gas, either with plastic on smaller scales, or on larger scales with rollers (Figure 4).

Figure 4. Single pass biofumigation system, with front mounted flail mower, rear mounted, rotary spading machine, with purpose built, powered, rear smearing roller. Credit AGROMOVIE youtu.be/SHKLFRr0GCI

The biotoxic chemicals in the plants are glucosinolates, which are sulphur containing organic compounds that are responsible for the pungency of mustard, cabbage and horse radish. They are present in the stem, leaves, roots and seeds of plants containing them. When incorporated into the soil, the glucosinolates are converted into isothiocyanates which have fungicidal, nematicidal and weed suppressive properties. The related chemical, methyl isothiocyanate, is a synthetic isothiocyanate, that serves as the active ingredient for chemical soil fumigants such as metam sodium. Thus, the same toxic compound found in synthetic fumigants can be supplied by plants. So while biofumigation is based on natural processes, the chemicals are still highly toxic, so, it only should be considered a technique of last resort. There are mustard cultivars that have been bred specifically for biofumigation to produce very large amounts of glucosinolates, which must be used for the best outcomes.

For both biofumigation and solarisation it is important to get good advice to ensure effective results and to avoid problems.

5.5.2.1. Further information

Wikipedia - Soil solarization en.wikipedia.org/wiki/Soil_solarization

Texas A&M AgriLife Extension - Soil solarization agrilifelearn.tamu.edu/s/product/soil-solarization/01t4x000004Ofpa

OSU Extension - Soil solarization for control of soilborne diseases extension.okstate.edu/fact-sheets/soil-solarization-for-control-of-soilborne-diseases.html

Wikipedia – Biofumigation en.wikipedia.org/wiki/Biofumigation

Cornell University, College of Agriculture and Life Sciences - Biofumigation for managing Phytophthora blight and other soil-borne pathogens vegetables.cornell.edu/pest-management/disease-factsheets/biofumigation-for-managing-phytophthora-blight-and-other-soil-borne-pathogens/

University of Missouri, Integrated Pest Management - Biofumigation for soil-borne disease control ipm.missouri.edu/MPG/2018/12/biofumigation/

5.5.3. Research examples

Fresh milk at higher concentrations was found to be as or more effective against zucchini squash powdery mildew (*Sphaerotheca fuliginea*) than fenarimol 0.1 ml/L or benomyl 0.1 g/L (Bettiol, 1999).

Over five years of trials in field pumpkins using milk to manage powdery mildew (*Podosphaera xanthii*), milk was found, depending on year, to be 0–70% as effective in reducing foliar symptoms and post harvest fruit rot and 40–50% as effective in increasing marketable yield as the chemical controls which always included the protectant fungicide chlorothalonil (1.6 kg a.i. ha^{-1} Bravo 90DG) and a sticker spreader and one of the following systemic fungicides azoxystrobin (0.4 kg a.i. ha^{-1} Quadris), myclobutanil (0.14 kg a.i. ha^{-1} Nova), benomyl (0.9 kg a.i. ha^{-1} Benlate 50WP) or triadimefon (0.1 kg a.i. ha^{-1} Bayleton) (Ferrandino & Smith, 2007).

Honey bees and bumble bees were used to vector a commercial formulation of *Trichoderma harzianum* to manage Botrytis cinerea on strawberries. The bee delivered *T. harzianum* provided better *Botrytis* management than *T. harzianum* applied as a spray, and achieved the same or a better level of management as the commercial fungicide vinclozolin applied at bloom. Strawberries collected from the bee-visited treatments averaged 22% more seeds and weighed between 26 and 40% more than berries in non-visited treatments (Kovach *et al.*, 2000).

Oilseed rape (*Brassica napus*) is attacked by the soil-borne fungal pathogens, damping-off and root rot (*Rhizoctonia solani*) and stem-rot (*Sclerotinia sclerotiorum*). A Trichoderma bio-inoculant was applied as a seed-coating to manage these pathogens. In two field experiments, one high one low pathogen pressure Trichoderma increased seedling emergence by 38% for the high and 35% for the low pressure sites. At the high pressure site, Trichoderma increased seed yield by 80%, primarily through a significant reduction in *S. sclerotiorum* infection. At the low pressure site, Trichoderma increased seed yield by 40%, primarily through plant growth promotion. Seed oil content was significantly ($P<0.05$) increased at the high pressure but not at the low pressure site (Kandula *et al.*, 2014).

Phytophthora capsici blight of pepper is exacerbate by co-infection with other pathogens including *Rhizoctonia solani*, *Fusarium oxysporum*, and *Fusarium solani*. A field-effective biocontrol strategy against *Phytophthora* blight of pepper was developed using three chitinolytic bacteria, *Serratia plymuthica* which is strongly antagonistic to *Phytophthora capsici*, *Chromobacterium* sp. which is strongly antagonistic to *Rhizoctonia solani*, and *Lysobacter enzymogenes* antagonistic to *Rhizoctonia solani* and *Fusarium* spp. The mixture suppressed *Phytophthora* blight under all field conditions (Kim *et al.*, 2008)

At four field sites in Germany a range of biocontrols / biopesticides against onion thrip (*Thrips tabaci*) were trialled on onion, leek and chives. The biocontrols were all commercially available products, and included Mycotal® *Lecanicillium muscarium* Ve6 (Koppert NL), PreFeRal® *Isaria fumosoroseus* (Biobest BE), Naturalis L® *Beauveria bassiana* (Intrachem IT), Nemaplus® *Steinernema feltiae* and Nemagreen® *Heterorhabditis bacteriophora* (both E-Nema DE). In onion PreFeRal + Nemaplus achieved a significant reduction in thrips, both the number of thrips/plant and the frequency of infestation 38 % compared to 93 % in the control. In leeks the number of thrips/plant was lowest for the treatments combing both fungi and nematodes, with the yield being 20 % higher for the treatments Nemaplus and Mycotal + Nemaplus than the control (Jung, 2008).

5.5.4. Further information

Understanding biostimulants, biofertilisers and on-farm trials merfield.com/research/2016/understanding-biostimulants-biofertilisers-and-on-farm-trials-ffc-bulletin-2016-v1-merfield-johnson.pdf (Merfield & Johnson, 2016)

The American Phytopathological Society, Biological Control of Plant Pathogens - apsnet.org/edcenter/disimpactmngmnt/topc/Pages/BiologicalControl.aspx

Biological control of plant diseases link.springer.com/article/10.1007/s13313-017-0481-4 (O'Brien, 2017).

6. Weed management

Agroecological weed management offers a large number of options for reducing agrichemical / herbicide use. As herbicides represent about half of total agrichemical use, because they are used in every crop, actively targeting a reduction in herbicide will be key to achieving the aims of A Lighter Touch and this project. In addition, over the last half century, an enormous amount of practical experience, scientific research, non-chemical weeding machinery and techniques have been developed, principally in organic horticulture. Most of this knowledge can be directly transferred to mainstream vegetable systems, often as drop-in solutions, to reduce reliance on and use of herbicides. Non-chemical weed management as a direct replacement for herbicides is thus a vital part of this project.

Further herbicide resistance is widespread in New Zealand both in terms of the number and type of resistant weed species and their geographical spread (as discussed in section 3.3). To minimise the build-up of herbicide resistant weeds, it is essential to minimise herbicide use, especially repeated use of the same mode of action (MoA). Non-chemical weed management techniques are thus a vital component of managing herbicide resistant weeds.

But, managing weeds with agroecology is a completely different ball-game to managing arthropods and diseases. That arthropods, pathogens and also weeds are all managed in conventional vegetable systems using the same technology of agrichemicals applied with sprayers, belies that biologically and ecologically they are all vastly different (as also noted at the start of pathogen management section 5). So, the agroecological approaches to weed management are completely different to those used for arthropods and those used for pathogens. This is in part due to the different relationship between weeds and crops compared with the relationship between crops and their arthropod pests and pathogens. Arthropods and pathogens are one level up the food chain (trophic level) than crops, i.e., they feed on them. Weeds in comparison are on the same level of the food chain, so they are competitors to crop plants. Most arthropods and pathogens also only attack a single species of crop plant or a few closely related crop species, e.g., brassicas. They exist in a one-to-one or few-to-few relationships. In contrast any one crop has tens to hundreds of weeds species that infest them and any one weed species can infest a wide range of crops. Crops and weeds therefore have a many-to-many relationship. This means that while for arthropod and pathogen management the management approaches many need to be quite specific to the crop and arthropod or pathogen species, e.g., a biopesticide that only kills a specific pest, for agroecological weed management, the management techniques mostly cut across weed and crop species, i.e., one weed management tool will work in many different crops. This is particularly true in vegetables as ecologically the crops and weeds are very similar, i.e., quick growing annuals. Thus for effective agroecological weed management it is critical to understand these biological and ecological differences and subtleties.

Non-chemical weed management is also a (very) large topic. Covering it in detail is beyond the scope of this report. Further sources of information are giving in the sections below.

6.1. Minimising the weed seed rain

The weed seed bank (i.e., weed seeds in the soil) is the heart of the annual weed problem as exemplified by the old adage “one years seeding – seven years weeding”. Just trying to manage annual weeds in cropping systems by only focusing on in-crop weeds does not address the core of the problem. This is particularly true when managing weeds with no or reduced herbicides. However, too often viable weed seeds are returned to the soil after crop harvest. There is now a considerable amount of research that shows the value of stopping the weed seed rain (i.e., return of viable weed seeds to the soil). For example Gallandt et al., (2010) found that by preventing weed seed rain in vegetables, they could reduce subsequent years weed seedbanks compared with other autumn treatments between 45% and 93% and weed seedling densities by 23% to 90%. The potential for reducing future weed management costs by preventing, or at least minimising, the weed seed rain is therefore considerable. Thus every effort to minimise the weed seed rain is required. For example, rather than cultivating weeds with viable seeds on them back into the soil, seeding weeds should be removed from the paddock.

6.2. Rotations

Clyde E. Leighty wrote in Soils & Men: Yearbook of Agriculture:

> "Rotation of crops…is the most effective means yet devised for keeping land free of weeds. No other method of weed control, mechanical, chemical, or biological, is so economical or so easily practiced as a well-arranged sequence of tillage and cropping."(Leighty, 1938).

In the era before herbicides rotations were clearly considered to play a key role in weed management. Current research also backs this up, e.g., (Liebman & Dyck, 1993; Anderson, 2010; Butkevičienė *et al.*, 2021).

However, to be effective for weed management, rotations need to contain sufficient ecological diversity, from a weed's perspective. This means rotating among:

- short term annuals such as vegetables,
- longer term annuals such as arable crops,
- spring vs. autumn sown crops,
- annual and perennial crops, i.e., pasture.

Many vegetable production systems only grow annual vegetables, some with arable break crops. This is not enough ecological diversity to provide meaningful weed management. A pasture phase of two to three years is a keystone in reducing the size of the annual weed seedbank. Such a pasture break would have many other ecological benefits in vegetable systems including reducing soilborne pests and pathogens and improving soil health. However, there are clear and large negative financial implications of taking high value horticultural land out of the most profitable crops and into low return crops or worse out of production. So, while a diverse rotation will have many benefits, including for weed management, economics often limit the ability to fully take advantage of them in vegetable systems.

6.3. False seedbeds

False seedbeds are where the soil is prepared into beds ready for planting, but, planting is then delayed for one to three weeks to allow the weeding flush to emerge. The weedlings are then killed with very shallow, minimal disturbance cultivation, and the crop is then planted. It is viewed as one of the primary non-chemical weed management techniques in vegetable systems (Merfield, 2015).

The advantages of false seedbeds are they only require simple, low cost machinery, the re-cultivation is quick and low draft, and they manage interrow and intrarow weeds including the most important close-to-crop-plant weeds. The disadvantages are that the planting delay of one to three weeks, which is lost crop production time and it also leaves soil unprotected from wind and rain erosion.

The key to successfully implementing false seedbeds is the getting the recultivation correct. If it is too deep, and brings up soil from below five centimetres it will bring up non-dormant, ungerminated weeds seeds, resulting in another weed flush. The cultivation also needs to achieve as close to 100% kill of emerged weedlings. There are a limited range of off-the-shelf equipment that can achieve this, including the milling bed-formers and spring tine harrows. Generally specifically designed 'false seedbed cultivators' achieve the best performance (Figure 5).

Figure 5. False seedbed cultivators. Left single roller and undercutter bar design, right, twin roller and A blade sweeps design.

See Merfield (Merfield, 2015) bhu.org.nz/future-farming-centre/information/bulletin/2015-v4/false-and-stale-seedbeds-the-most-effective-non-chemical-weed-management-tools-for-cropping-and-pasture-establishment for more information.

6.4. Mechanical in-crop weeding

Mechanical in-crop weeding is well placed to be a direct substitute for herbicides in many vegetable crops.

6.4.1. Mechanical weeding and herbicides – complimentary weather windows

One advantage of mixing herbicides and non-chemical approaches is the optimum weather windows of the two approaches are highly complementary, giving growers much bigger weather weeding windows. Herbicides cannot be applied when the wind is too low or too high due to spray drift, in really hot conditions and/or if rain is imminent. In comparison, many mechanical weeding techniques are most effective in hot windy conditions. Therefore having both options means that effective weeding can be undertaken under a much wider range of weather conditions.

6.4.2. The importance of weeding to weed size not crop stage

A key limitation of most mechanical weeders is their effectiveness rapidly declines with increasing weed size. While for herbicide based weed management it is often crop stage or other aspects of crop timing, e.g., time since planting, that determines when to spray. In mechanical weeding it is weed size that is paramount. This is especially true of intrarow weeders (see below). The best time to mechanically weed is when the weeds are at the newly emerged cotyledon stage. Before emergence, often called 'white thread stage' killing weedlings by burial is less effective. Once weeds have their first true leaves they become exponentially harder to kill as each set of true leaves emerges.

6.4.3. Contiguous and incontiguous in-crop weeders

In-crop weeders are divided into two broad approaches: contiguous and incontiguous.

Contiguous weeders weed the whole paddock surface, thus apply the weeding technique to both crop and weeds. The crop must be tough enough to tolerate the weeding technique or it will damaged or killed. Generally contiguous weeders are mostly used in arable. One design – the spring tine harrow – can be used in vegetables and fills a number of important niches.

Incontiguous weeders, have gaps for the crop to pass through. These were commonly called interrow hoes, but, that is now an inaccurate name as there are an increasing number of intrarow weeding tools that are mounted on 'interrow hoes' so that they weed the interrow and intrarow at the same time but using different tools.

Generally the tools weeding the interrow are very aggressive, e.g., horizontal knife blade hoes, and they will kill the crop if the hoe is not correctly aligned with the crop rows.

The intrarow weeding tools, apply the same technique to both crop and weeds (like a contiguous weeder), thus the crop needs to be tough enough to survive the weeding treatment that kills (at least some) of the weeds.

With modern weeding machinery, management of interrow weeds is now considered straight forward with the right equipment. Management of intrarow, especially 'close-to-crop-plant' weeds, which have the biggest competitive effect are considered more challenging but manageable.

A key part of successful mechanical weeding is the use computer guidance systems for incontiguous weeders. This has turned what used to be a specialised field operation, often requiring tool-carrier tractors, into a standard three-point-linkage task. Computer guidance also allows for vastly bigger weeding machinery along with much faster and more accurate steering.

6.4.4. Computer guidance systems

The computer guidance systems are based on two approaches: RTK-GPS and computer vision.

RTK-GPS was originally designed to just steer the tractor, but a few manufacturers now offer implement steering (double steering) where both the tractor and the implement are independently steered. Vision guidance originally was designed to only steer the implement, but, there are now tractor steering systems based on computer vision.

GPS systems require that the crop is drilled using GPS so that the weeder can then follow the GPS lines. Vision systems follow the actual crop rows so can work with crops planted with hand-steering. The two systems are complimentary. GPS system ensure the most accurate and straight planting possible allowing maximising the potential of mechanical weeding. GPS is a key means of implementing controlled traffic farming (CTF, see section 3.5.3.1). GPS can also be used before the crop has emerged when vision system don't have the crop to guide them, for activities such as band spraying (see below). Vision systems however, can achieve higher accuracies than GPS systems, and, can be used on tractors that are not setup with full RTK GPS autosteer.

GPS double steer systems that use side-shift for steering (as opposed to ground engaging steering wheels) have a major advantage over just tractor based autosteer, in that the implement is aligned with the crop row while it is still lifted off the ground, even if the tractor is not lined up with the beds. This provides a major improvement in speed and accuracy at the start of rows.

6.4.5. Contiguous weeders – the spring tine harrow

There are four main designs of contiguous weeders. These include:

- The spring tine harrow,
- Spoon weeder (American name = rotary hoe), www.sare.org/publications/steel-in-the-field/row-crop-tools/rotary-hoe-standard/
- Einböck Aerostar-Rotation®, www.einboeck.at/en/products/crop-care/weeding-technology/aerostar-rotation
- CombCut®, lyckegard.com/en/products/combcut/

Of these, only the spring tine harrow is considered a viable weeder in vegetable systems. The spoon weeder and Aerostar-Rotation are considered too aggressive and the CombCut® is designed to cut think stemmed weeds like thistles out of thin stemmed crops like cereals.

Developed over 50 years ago, spring tine harrows are produced by many manufacturers. They consists of a large number of thin spring steel rods which rake through the soil surface like a giant garden rake Figure 6 and Figure 7.

Figure 6. Large spring tine harrow with pneumatic seeder unit.

Figure 7. Spring tine weeder detail: Left, modular ‘wishbone’ ground following system. Right, details of spring tines.

Most machines are too aggressive for vegetable production system, but, a few manufacturers have designs with very precise depth control and thin lightweight tines that minimise crop damage. These still cannot be used in just any vegetable crop, for example they will cause considerable damage to young lettuce, but, for tougher crops, such as cabbages, and ,more robust thin vertical crops, e.g., leaks, onions, sweetcorn, they can be highly effective. Their key advantages are:

- as contiguous weeders they don't need guidance systems (see above) so can be hand steered,
- they weed both the interrow and intrarow including close-to-crop-plant weeds,
- due to large sizes good to high work rates can be achieved,
- When coupled with a pneumatic seeder, they can be used for final cultivation and seeding at the same time, as well as quickly establishing subsidiary crops, undersowing, etc.

Spring tine weeders are therefore considered valuable machines for vegetable production even though they were originally designed for arable crops.

Michigan State University, Department of Horticulture has a detailed video on spring tine harrows youtube.com/watch?v=X57zjHNuBeE

6.4.6. Incontiguous weeders (interrow hoes)

Incontiguous weeder manufacturers have nearly all converged onto a single design based on modular parallelograms (Figure 8).

Figure 8. Modular, parallelogram interrow hoe with white dashed line indicating the parallelogram pivot system.

The units are called parallelograms due to the parallelogram pivot system that ensures the weeding frame and tools mounted on them are kept parallel to the ground at a optimum depth. The modular approach allows for any row crop, from the narrowest to the widest spacings to be accommodated, and for a wide range of machine widths, e.g., up to 25 m wide.

The combination of computer guidance systems and well-designed modular incontiguous weeders means that any crop grown in rows can be successfully interrow hoed. The primary limit is that for row spacings less than 10 cm less than half the field surface consist of the interrow and is weeded, with the majority of the field thus being intrarow and unweeded. 15 cm is thus considered the minimum viable interrow spacing for interrow hoeing.

6.4.7. Intrarow weeders

As discussed above, the final frontier for mechanical weed management is the intrarow and particularly close-to-crop-plant weeds. The last 30 years has seed the advent of a diverse range of intrarow weeders that have nearly confined manual hand hoeing and hand weeding to the dustbin of history (Merfield, 2014).

A key concept in intrarow weeding i 'close-to-crop-plant weeds'. Weeds in the interrow are now considered easy to control so can't compete with the crop as they are dead. Intrarow weeds that are some distance from the crop plants wont have any competitive impact on the crop until they grow to sufficient size that their roots mingle with the crop roots or their foliage starts to shade the crop. This may well take some time, and may well then fall outside the critical control period (see section 6.9.4) so they never impact yield. It is thus the close-to-crop-plant weeds that establish right next to the crop plant that will have the largest competitive effect as their roots and foliage will be interfering with the crop very quickly after crop establishment. It is therefore close-to-crop-plant weeds that are the most important to control, and also the most difficult.

6.4.7.1. Mini-ridgers

Mini-ridgers work by burying small weedlings. Research has show than just 1 cm of soil covering a weed, pretty much regardless of its height, is lethal, while having just 2 cm of the crop standing free of soil will allow 100% survival (Merfield, 2018b; Merfield *et al.*, 2020). The mini-ridgers themselves are the simplest possible engineering, just being two pieces of flat bar welded horizontally onto a leg to make a V shape (Figure 9).

Figure 9. Mini ridgers on horizontal brush hoe (left), and different designs (right) from left to right, low profile for small ridges, large for big ridges, and low angle for high speed use.

The height of the bar determines the height of the ridge so very precise control of the ridge height can be achieved with different height bars. When mini-ridgers are used with an interrow hoe they can achieve close to 100% control of weeds across the whole bed, including the most important close-to-crop-plant weeds. They are considered both the most effective intrarow weeders and the cheapest.

See bhu.org.nz/future-farming-centre/information/bulletin/2018-v2/mini-ridgers-lethal-burial-depth-for-controlling-intrarow-weeds for detailed information on mini-ridgers.

6.4.7.2. Finger weeders

Finger weeders consist of pairs of star like rotating fingers position in the intrarow (Figure 10). They are rotated by short soil engaging tines which causes the ends of the fingers to rotate faster than ground speed causing them to push and pull the soil in the intrarow killing small weedlings.

Figure 10. Finger weeders. Left weeding cabbage, right showing detail.

The weeding fingers are made of a wide range of materials, from thick hard plastic, through rubber sheets through to even paint brushes. This allows for a very wide level of weeding aggressiveness from brutal to very gentle. Finger weeders are available for both annual and perennial crops. From an engineering perspective they are simple, robust and easy to adjust. They are also a great combination with mini-ridgers to push up and pull down ridges, doing on a small scale, the traditional approach to potato weeding of pushing up and pulling down the ridges. All these attributes have made finger weeders a very popular tool across a wide range of farming systems.

For more information on finger weeders and other intrarow weeders see bhu.org.nz/future-farming-centre/information/bulletin/2014-v4/the-final-frontier-non-chemical-intrarow-weed-control-for-annual-crops-with-a-focus-on-mini-ridgers and also Michigan State University, Department of Horticulture has a detailed video on finger weeders youtube.com/watch?v=38uKyhJMT0Q.

6.4.7.3. Intrarow band herbicides

Intrarow band application of herbicides combined with interrow hoeing is considered a valuable means of reducing total herbicide use, while maximising the value of herbicides in the intrarow area where mechanical weeding is more challenging. Computer guidance systems are valuable to ensure precise and accurate placement of the herbicide bands and to ensure they match the drill rows.

6.5. Robotic weeders – the revolution

There has been a revolution in weeding robots starting around 2020. This is due to the use of deep learning artificial intelligence (AI) networks for plant identification, such as Google Deep Mind.

The 1900s saw the first computer vision guidance systems that could track crop rows and guide interrow hoes. These are called Level 1 robotic weeders. This progressed in the 2010s with computer vision systems that could identify every crop plant and weed around them thus weeding both interrow and intrarow. These are called Level 2 robotic weeders and examples include the K.U.L.T. 'Robovator' (www.kult-kress.com) and Garford Farm Machinery Ltd.'s 'Robocrop' (garford.com). These are now well farm-proven technology and are direct herbicide replacements that are available now.

Level 3 weeders identify the location of every plant, then using advanced artificial intelligence to determine which are crop plants and which are weeds and robot then individually kills each weed plant, using a range of different techniques, e.g., mechanical, micro-spot spraying organic herbicides and lasers. Examples include Greentech Robotics Ltd.'s 'WeedSpider' (greentechrobotics.com), Carbon Autonomous Robotic Systems Inc.'s 'LaserWeeder' (carbonrobotics.com) and Kilter AS's 'AX1' (kiltersystems.com).

While still in their infancy, Level 3 robotic weeders have the potential to completely replace not only synthetic herbicides but also most other non-chemical weeding technologies in vegetables. Level 3 robots are now working commercially overseas, and while it is likely to be several years before they are widely available in New Zealand they could be revolutionary for weed management. See fira-agtech.com and ducksize.com for more information on agricultural robots.

6.6. Research examples

While there are many mechanical weeding research papers, they are considered less useful as examples of solutions than for other pests. This is because they are often focused just on one machine or technique in one crop in unrealistic conditions, i.e., they don't replicate how growers actually use weeders. This often then results in unfavourable results compared to real-world use. This is because scientists often follow herbicide research methodology which is considered inappropriate for mechanical weeder research. Also with mechanical weeding it is immediately apparent if a weeder is having the desired result, i.e., killing the weeds, by the operator looking to see what the weeder has done when used in the paddock. Indeed checking if the weeder is working correctly, i.e., killing weeds, is a vital part of machinery setup and adjustment. Thus there is often limited value in undertaking research into how well a particular weeder works as growers can immediately see this for themselves when using the machines in the paddock.

6.7. Further information

Physical Weed Control Forum: Deconstructing the 'Art' of physical weed control by the University of Maine and Michigan State University is a relatively new forum aiming to be a hub for a wide range of physical weeding resources forum.physicalweedcontrol.org/

Manage weeds on your farm: A guide to ecological strategies (Mohler *et al.*, 2021). An excellent and detailed book on ecological weed management from three of the worlds leading agroecological weed scientists. sare.org/resources/manage-weeds-on-your-farm/

Integrated weed management in organic farming by Charles Merfield (Merfield, 2018a) expands on the information giving in this report. This book chapter has to be purchased for US$40. sciencedirect.com/science/article/pii/B9780128132722000057

Integrated weed management in arable crop systems (Merfield, 2019a) while focused on arable crops and addressing herbicide resistance it still has a range of useful information for vegetable systems merfield.com/research/2019/integrated-weed-management-in-arable-crop-systems-2019-merfield.pdf

Weed biology and weed management in organic farming (Lundkvist & Verwijst, 2011) is a good overview and it also covers stacking tools and multiple passes, with a section on putting it all together intechopen.com/chapters/25094

Michigan State University, Department of Horticulture, Mechanical Weed Control Youtube channel has a number of detailed and unbiased videos explaining and demonstrating a number of mechanical weeders youtube.com/channel/UCH-k889oYbUaEznvgiDtrOQ

A review of knowledge Interrow hoeing and its associated agronomy in organic cereal and pulse crops by James Welsh, Nick Tillett, Matthew Home and John King (Welsh *et al.*, 2002) while now two decades old contains a wealth of detailed information, some still not captured in more recent publications orgprints.org/6673/1/OF0312_2234_FRP.pdf

Steel in the field: A farmer's guide to weed management tools (Bowman, 1997)while this is now a quite dated publication it was the first of its kind and it gives a handy overview the range of weeders types .sare.org/resources/steel-in-the-field/

6.8. Nutrient (fertiliser) timing and placement

Traditionally fertilisers have been spread across the whole paddock. There are many reasons to re-evaluate this practice. One reason is that fertiliser applied to wheelings (especially in controlled traffic farming (CTF) systems (see section 3.5.3.1) are not used by the crop and are therefore wasted. Another reason is that when applied to the surface, the weeds get first access to the nutrients, because they are small and thus have more of their roots close to the soil surface. By injecting / banding fertilisers deeper into the soil and close to the crop, the crop has first access to the nutrients and therefore gains a competitive advantage over the weeds (Figure 11).

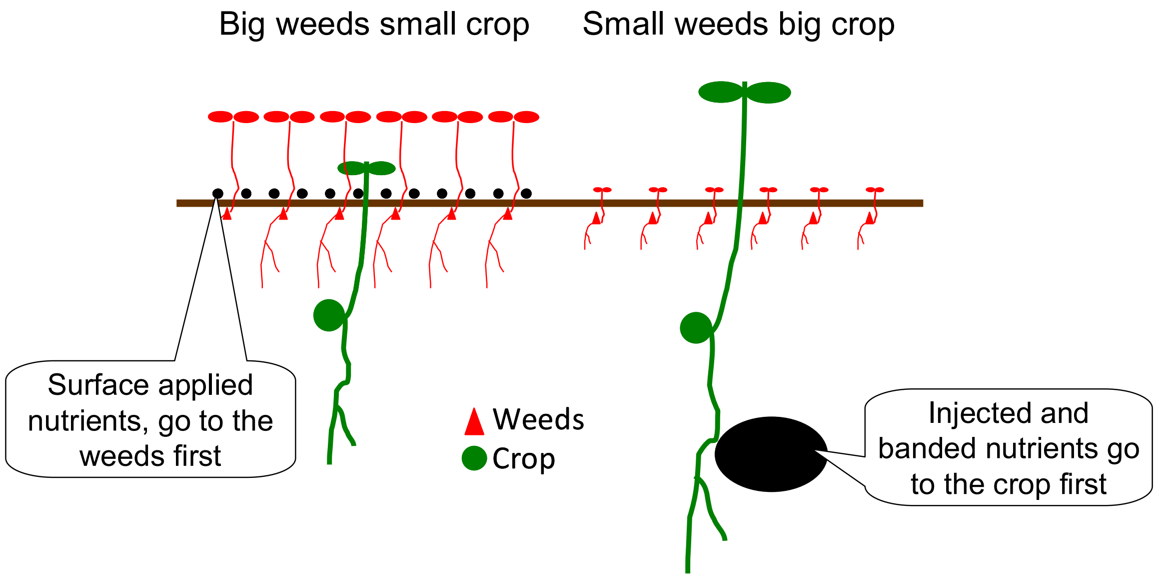

Figure 11. The comparative impact on weed growth of surface compared with injected and banded nutrients.

With multiple pressures on fertiliser use, moving to precision application, through banding, injection, and correct timing, will be increasingly important. Injected and banded nutrient placement has revolutionised weed management on many organic farms.

6.9. Plants vs. weeds – the need for system redesign and agroecology

While there are many impressive technological advances in mechanical weeding, which can achieve as effective weed management as herbicides. However, the overall outcomes they achieve, in terms of monocultures of vegetables surrounded by bare soil are increasingly being questioned as to their long term viability. Bare soil is at increasing risk of wind, and especially water erosion, in the increasingly frequent high intensity rainfall events (i.e., floods) occurring in New Zealand. As soil is a growers primary capital asset, which cannot be economically replaced, soil loss directly represents the loss of a farm's productive capital. Lost soil typically ends up in waterways with multiple negative environmental outcomes. Bare soil is also a risk in other ways, such as loss of soil quality, resulting in poorer yields, needing more irrigation and fertiliser, and a climate change risk due to the loss of soil carbon.

6.9.1. Redefining weeds

There is thus a need to move not just to technological solutions to weed management but preferably more ecological techniques (Gliessman, 2014). This is based on a re-evaluation of what are weeds. For example, deliberately leaving weeds among crops has been shown to provide multiple ecosystem services while maintaining yield (Adeux *et al.*, 2019), and weeds contribute to sustaining crop yields through their roles in supporting beneficial biodiversity and soil fertility (Jordan & Vatovec, 2004; Ziska & Dukes, 2010). A recent paper has suggested moving on from the definition of a weed being 'a plant where it is not wanted' to weeds being plants that are causing 'significant harm' (Merfield, 2022). The rest of the plants in the field are then defined as 'other plants' or 'aliae plantae' and ignored.

While the idea of identifying weeds as those 'causing significant harm' and only controlling those and leveling the aliae plantae that are not causing 'significant harm' alone, has good theoretical and scientific merit, in vegetable production system implementing this concept can be at best described as challenging. A far more practical approach is to deliberately add non-cash crop plants to the production system that will out compete weeds. This is the concept of 'plants vs. weeds'. Most of these are forms of subsidiary cropping, such as living mulches. The same approaches are also important for arthropod pest management and to a lesser extent plant pathogen management, as discussed earlier in this report.

6.9.2. Plants vs. weeds is biocontrol

The plants vs. weeds concept of using good plants to fight the weeds is a form of conservation biocontrol using the ecological interaction of competition (see section 3.1 for the five types of interactions). However, most agroecological weed management is not viewed through a conservation biocontrol lens, which, misses some potentially valuable insights.

Weeds can also be managed using the two other forms of biocontrol.

Augmentation biocontrol of weeds, both inundative and inoculative has generally not been successful. No known example of inoculation management of weeds has been found (e.g., regular releases of arthropod pests of a weed). Inundative approaches are almost exclusively restricted to the bioherbicides, i.e., a plant pathogen (such as fungi or bacteria) that is applied as a spray, the same as chemical herbicides. Bioherbicides have a very poor commercial track record, with most of the few that have made it to market, being withdrawn due to issues with efficacy or profitability. The challenge is that most weed pathogens, and therefore bioherbicides, are host specific so only kill one or a few closely related weed species. However, any given crop will be infested with a large range of weed species. Multiple bioherbicides would thus need to be used in a single crop, which would likely be cost prohibitive and impractical. This contrasts with host specificity in bioinsecticides, which is highly valuable as it avoids killing non-pest arthropods species, especially beneficials that attack crop pest arthropods.

Introduction (classical) biocontrol has achieved some spectacular examples of highly effective weed management across the world and in New Zealand. However, it is outside the control of growers, so is not something they can undertake themselves.

6.9.3. Subsidiary crops between cash crops

Growing subsidiary crops in-between cash crops, i.e., in fallow periods, particularly cover crops grown overwinter, is the ‘traditional’ use of subsidiary crops. For many growers the main reason to grow such subsidiary crops is to protect / enhance soil health and fix nitrogen. However, there is also considerable potential for subsidiary crops between cash crops to provide weed management benefits. This is via these main ecosystem functions:

- Suppression of weeds through competition and sometimes allelopathy, that would otherwise flourish in a fallow,
- Reducing / minimising weed seed rain,
- Increase the depletion of the weed seed bank, through predation, pathogens, allelopathy and other biological means of seed loss,
- Provision of dead mulch, e.g., for roller crimping,
- Incorporation to inhibit or retard weed seed germination, e.g., through allelopathy (see also biofumigation section 5.3).

Key references: (Sustainable Agriculture Network, 2007; Teasdale *et al.*, 2007; Lemessa & Wakjira, 2015; Lowry *et al.*, 2018; Osipitan *et al.*, 2019).

As subsidiary crops grown between cash crops have multiple benefits, both on and off farm, they are considered a key technique to integrated into vegetable systems in New Zealand and to be demonstrated as part of this project.

6.9.3.1. Research examples

In Europe, a meta analysis of using a crimper roller to terminate subsidiary crops compared with cultivating them in found weed density was reduced by 35.1% on average (Navarro-Miró *et al.*, 2019).

In New York state, USA, trials of pure legume and grass-legume cover crops showed the importance of grass-legume mixtures to minimise weed biomass in cover crops (Daniel *et al.*, 2011).

Increasing the functional diversity of cover crop species in Mediterranean farming systems increased weed suppression and biomass by an average of 37% (Ranaldo *et al.*, 2020).

In organic vegetable systems in California, USA, a mixed cover crop consisting of bell bean (*Vicia faba*), woolypod vetch (*Vicia dasycarpa*), purple vetch (*Vicia benghalensis*) and pea (*Pisum sativum*) and oat (*Avena sativa*), when weeds were abundant, weed biomass declined linearly from approximately 300 kg/ha to <100 kg/ha as seeding rates increased from 112 to 336 kg/ha (Brennan *et al.*, 2009).

In Virginia, USA, over three years, a no-till, raised bed, potato production system using mulch from over wintered cover crops was developed that with yields equal or higher than in no-mulch tilled control plots with weed biomass kept below the level where yield suppression occurs (Morse, 2006).

In North Dakota, USA, at two sites, in irrigated potatoes, five over winter cover crops were terminated by either glyphosate, disk harrows or rotary hoe, achieved high levels of weed management with the same yields for all three termination approaches at one site and higher yields for rotary hoe at the second site (Mehring *et al.*, 2016).

6.9.4. Subsidiary crops - living mulches

Living mulches are subsidiary crops that are grown underneath the cash crop (Müller-Schärer & Potter, 1991). They are viewed as having considerable potential in vegetables, as they not only can assist with weed management, they have multiple benefits including:

- Protecting soil from wind and rain damage and erosion,
- Help maintain and improve soil health, e.g., increase organic matter, infiltration,
- Leguminous living mulches can fix nitrogen which can be directly transferred to the crop (Meng *et al.*, 2015; Wang *et al.*, 2016) as well as following crops,
- Reduce n leaching particularly in the post harvest period, and especially if otherwise fallow,
- Provide conservation biocontrol services of arthropod pests, such as SNAP and interrupting arthropod pest host searching behaviour (Finch & Collier, 2000, 2003),
- Help manage soilborne pests (arthropods, nematodes, pathogens) (e.g., Theunissen & Schelling, 2000).

This makes living mulches a highly agroecological approach. Key references: (Müller-Schärer & Potter, 1991; Hartwig & Ammon, 2002; Canali *et al.*, 2017; Bhaskar *et al.*, 2021; Westbrook *et al.*, 2022).

The main desirable features of living mulch species are:

- Commonly available species (inexpensive) which typically means pasture species and a few arable species,
- Sufficient amount and density of foliage to suppress and out compete weeds,
- Quick emergence,
- Fast initial growth, especially to achieve canopy closure / soil cover,
- Short height / prostrate,
- Different root system architecture / morphology to cash crop to minimise root interaction / competition,

- Nitrogen fixing,
- Low nitrogen demanding,
- Provides conservation biocontrol. (Müller-Schärer & Potter, 1991).

In vegetables they are best suited to larger crops, especially those where only the upper part of the plant is harvested, e.g., brassicas, those grown on wider spacings where canopy closure can take some time, e.g., courgettes, sweetcorn, field tomatoes, those with a long growing period, especially over winter, and any crop where plastic sheet mulches are used. Crops unsuited to living mulches are higher density crops that quickly achieve ground cover, e.g., radish, or where the whole foliage is harvested which could be contaminated by the mulch, e.g., lettuce.

While there are potentially many benefits of living mulches, finding the right living mulch species for given crop at a given time of year is not easy. There are plenty of examples in the literature where living mulches reduced cash crop yield (sometimes dramatically) and had other negative effects. However, a number of these were using living mulches that would generally be considered unsuitable by experienced living mulch practitioners, so some are failures of understanding. These include cereals, especially large allelopathic species such as ryecorn (*Secale cereale*) grasses in general and shallow rooted species being used as living mulches.

The main challenge is finding living mulch species that does not compete with the crop and reduce yield. Though some yield reduction may be compensated by other gains, e.g., reduced spending on agrichemicals and weeding, so although yield is slightly reduced, profit may increase. Most successful living mulch species are low growing compared with the crop, so generally above-ground / light competition is all in the crops favour. This means most if not all the competition is underground / root competition, which is why having different root systems, e.g., tap root vs. shallow roots, for the living mulch and the cash crop is critical.

There are different approaches to the timing the planting of the cash crop and living mulch:

- Perennial living mulch – where the living mulch is established first, and may maintained for multiple years, with the crop being planted into the mulch. This can include directly sowing the crop into the living mulch, e.g., after grazing / mowing, or killing strips of living mulch and strip tilling in the crop,
- Synchronized sowing where the cash crop and living mulch as planted at the same time,
- Relay intercropping, where the living mulch is planted after, often well after, the crop was planted.

A useful concept when considering the relative planting times is the 'critical control period' which is the period in the crop growth cycle during which weeds must be controlled to prevent yield losses Figure 12 (Knezevic *et al.*, 2002).

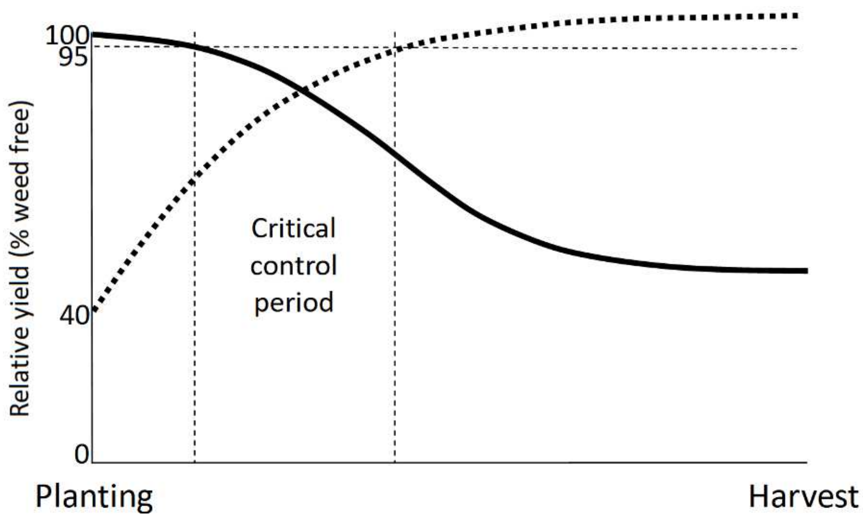

Figure 12. The critical control period, based on achieving 95% yield compared with completely weed free crop. The solid curve is yield where weeds are allowed to grow among the crop from planting but then killed at that date, the dotted curve is yield where the crop is kept weed free up to that date, but weeds are then allowed to grow among the crop. The critical control period is thus between the date after establishment where the initially weedy, then weed free, crop yield is 95% and the date where the initially weed free then weedy crop yield is 95%.

The critical control period thus indicates when the crop is most susceptible to competition. Typically this is a few weeks after planting to about the a third of the crops life (Figure 12). However, the critical period is highly variable, with different crop species, even cultivars, weed species & populations, soil and climate all potentially impacting the actual critical control period for a given crop. It is also based on the assumption that most weeds will emerge at planting, due to cultivation / termination of the previous crop, and that they will be evenly distributed, i.e., some will be close to crop plants, others some distance from crop plants. Thus it is more a general concept that the key time to keep crops weed free is from a few weeks post establishment to about a third to half the life of the crop.

The critical control period is not applicable to perennial living mulch systems (see above) where the crop is being sown into an existing crop. Almost without exception if a crop (cash and subsidiary) is sown, or even transplanted, into existing vegetation, even if it has been heavily defoliated or otherwise set back, the planted crop will be strongly out competed, even killed, by the existing vegetation. There is increasing anecdotal evidence that suppressing perennial living mulches, e.g., by mowing, compared with mature mulches (i.e., not increasing above ground biomass) may actually increase root competition as the living mulch draws on soil water and nutrients to regrow.

What this indicates for living mulches is that delaying establishment towards the end of the critical control period will minimise the risk of the living mulch competing with the crop (Theunissen & Schelling, 2000). Müller-Schärer & Potter (1991) recommend delaying sowing until halfway through the cash crops life. However, this means there is no living mulch when the crop has the least ground cover, leaving soil unprotected.

Other main factors impacting competition includes:

- Living mulch species. The living mulch ideally needs to have both foliar and root morphologies that don't compete strongly with the crop, e.g., low growing foliage, and tap roots with limited sideways rooting (Leoni *et al.*, 2020).
- Spatial arrangement, e.g., planting the living mulch at a distance from the crop (i.e., not right next to the crop) allows more time before the crop and mulch start interacting / competing with each other.
- Using leguminous living mulches so there is minimal nitrogen competition, and ideally supply of N from the mulch to the crop can have a considerable impact on competition.

- Changing fertiliser and irrigation to compensate for the extra living mulch plants can also help manage competition (Bhaskar *et al.*, 2021).

Living mulches can also be directly managed to limit competition (Bhaskar *et al.*, 2021). This can be by both physical and chemical means, e.g., mowing, band spraying herbicides. The mulch may just be set back by mowing or killed completely to leave a dead mulch. This also allows the living mulch to be established earlier in the crops life during the critical control period, or even at planting, providing benefits such as soil protection and weed competition earlier in the crops life, often when it is most critical, but, preventing the living mulch becoming too competitive later on, (Gibson *et al.*, 2011; Bhaskar *et al.*, 2021; Sportelli *et al.*, 2022).

6.9.5. Research examples

In a meta-study of legume living mulches in arable crops, lower weed biomass and a higher yield (win- win situation) than non-weeded or weeded control treatments was found in 52% and 36% respectively of cases, while higher weed biomass associated with a lower yield (lose-lose) than non-weeded or weeded control treatments was observed in only 13% and 26% cases (Verret *et al.*, 2017).

Over two years in four European countries living mulch was found to reduce nitrate leaching under both cauliflowers and leeks (Xie *et al.*, 2017). As part of the same experiments, in Denmark using white clover (*Trifolium repens*) and ryegrass (*Lolium perenne*) living mulch reduced aphids on cauliflower and in Italy, there was a very high level of caterpillar parasitisation with 88% parasitism in the living mulch of burr medic (*Medicago polimorpha*) compared with 63% in the monoculture cauliflower (Depalo *et al.*, 2017). This demonstrates the multiple benefits of living mulch.

6.9.6. Further information

DiverIMPACTS - Diversification through Rotation, Intercropping, Multiple Cropping, Promoted with Actors and value-Chains towards Sustainability diverimpacts.net/toolbox.html

Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability plant-teams.org

ReMIX: Redesigning European cropping systems based on species MIXtures remix-intercrops.eu

Agricology cover crop and living mulch wiki agricology.co.uk/resources/cover-crop-and-living-mulch-wiki-0

7. Conclusions

This report highlights the large number of agroecological pest management techniques that can be used to reduce agrichemical use in New Zealand vegetable production systems. Some techniques are suitable for growers to start testing themselves, ideally on small areas to start with to check they work and build up expertise. Others will require more research to check and validate them before commercial uptake. It is hope that this report therefore provides a clear roadmap for the way ahead.

8. General further information sources

FAO https://www.fao.org/agroecology/

Agroecology for Europe https://www.ae4eu.eu/

European association for agroecology https://www.agroecology-europe.org/

SureVeg https://tporganics.eu/sureveg/

UC Santa Cruz Center for Agroecology https://agroecology.ucsc.edu/

Agricology https://www.agricology.co.uk/

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