Identification of potential alternatives to Metham Sodium

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RMCG

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Purpose of the report:

This study provides reference information for the vegetable industry. It seeks to describe the drivers for Metham Sodium (MS) use in Australia, discusses issues around MS safety hazards and efficacy, and offers information on alternatives.

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Media Summary

The bigger picture

The continued reliance on chemical soil fumigants such as Metham Sodium (MS) can largely be attributed to consumer demand for low cost, good quality, nice-looking vegetables. This drives the need for intensification and specialisation in the vegetable industry to maintain economical viability. Ironically, consumer expectations and market requirements may also affect the continued acceptability of using 'old style' broad-spectrum fumigants even if the products are not deregistered. A review or deregistration of MS is not planned at the time of writing this report.

Unfortunately, intensification has, in many cases, changed soil conditions and reduced inherent disease suppressive soil properties, thus reinforcing a reliance on fumigation to deal with soilborne diseases, pests and weeds. Much stated drivers for continued MS use, besides the need for 'attractive', inexpensive vegetables, are its apparent broad-spectrum efficacy and low cost.

Several growers are concerned about health affects of MS, having had 'a whiff of it', especially since one of the main reasons for strict regulation or discontinuation of MS elsewhere is its toxicity to humans. Producers also mention potential environmental effects as an issue but they usually have not experienced or investigated them. In addition, MS can be subject to enhanced biodegradation with specialist microbes able to inactivate it quickly. Many growers are aware of this risk but do not know whether they are affected.

Replacing a broad-spectrum fumigant with integrated methods requires growers and their advisers to understand the complexity and risk profiles of all pests and diseases that may affect their crops. Integrated solutions are not simple 'drop-in' replacements. These need to be site-specific and adjusted to individual farm circumstances and growers' personal preferences. This often takes time. The economics of most MS alternatives require looking at cost / benefits over longer timeframes and use of more complex calculations than those for annual crop gross margins. Economic survival however is often a year-to-year issue for vegetable producers; this prevents many from taking a longer-term view.

Chemical alternatives to Metham Sodium

Some chemical fumigant alternatives to MS are registered in Australia e.g. Telone (1,3-D) and Telone C35 (1,3-D and Chloropicrin), which offer a similar level of effectiveness, yet are more costly and present their own suite of problems such as environmental impacts and enhanced biodegradation issues similar to MS. They are also 'old style' chemicals and thus do not offer a suitable long-term alternative for growers. Additional chemical fumigants registered in other countries have been tried here. They are also toxic to humans and the environment; thus they do not offer a viable alternative.

One long known fertiliser and soil conditioner, calcium cyanamide, can affect germinating seeds, small upcoming weeds and soil borne pathogens. It has no negative environmental effects and can be integrated with other approaches.

One new chemical fumigant, Ethanedinitrile (EDN), may become available for vegetable producers in the future. It has been developed with CSIRO and BOC and is available as a fumigant in Germany.

The choice of specific nematicides and fungicides for soil application is limited; using several of them plus herbicides to control all risks is certainly more expensive and is often considered less reliable than a ‘one-for-all’ fumigant. Most herbicides are ‘old style chemistry’ and new products for vegetables are not on the horizon, which is a concern.

The use of improved seed dressing technology and products will help in crop establishment and resilience but on its own it will not be sufficient to protect crops when disease pressure is high.

Non-chemical alternatives to Metham Sodium

The development of effective biocides appears promising and products, including a fumigant, are becoming available in the US. Biocides may need to be used as part of an overall adjustment in soil and crop management and not as a simple product replacement. Costs may be higher than for MS.

Biofumigation crops seem to provide a feasible alternative if growers can find the right species and management approach to include them into a production system. They can control soil borne diseases and weeds. The use of biofumigation is more expensive than chemical fumigation on comparison of straight input costs to an annual crop, however, the longer-term benefits of improving soil condition are not considered in this direct cost comparison, mainly because there is no reliable data to do so. Not all producers can look at longer-term, wider benefits if cost pressures are immediate.

Many growers have used ‘soil or plant health enhancing products’ in their systems when moving away from MS. However, objective scientific data on these products is still limited and can be debatable. These other products have not been included in this review. A watching brief is recommended.

Some information exists on the effect of biochar and organic amendments (e.g. quality composts) on soilborne disease suppression. Cost benefit analyses for their use in vegetable systems are required.

Integrated crop protection (ICP)

Integrated approaches (ICP) offer alternatives to the management of soilborne diseases. They rely on practice change and the integration of multiple approaches. Any single one of the ICP alternatives, when looked at as a ‘drop in’ will lack the cost effectiveness, broad efficacy, and reliability of effective chemical fumigants. It is however possible to combine a range of integrated approaches to achieve an economically viable production system (Martin 2003). Carrot growers in Victoria, South Australia and Queensland who decided to produce without MS have demonstrated this. In many European countries where Methyl Bromide had been banned for a long time in vegetables and MS is being phased out, growers have worked with integrated methods, especially biofumigation, to manage soil borne diseases for some time. The change to integrated practices there was supported by RD&E.

The adoption of an ICP approach using biofumigation, proven amendments or ‘enhancers’ and biocides/biological control as they become available, presents opportunities for vegetable growers relying on MS. Being proactive in implementing ICP means that enhanced biodegradation or pesticide resistance will be avoided. ICP approaches can be maintained over the long term despite potential changes to chemical regulations or MRLs in Australia and overseas.

Extension and R&D

Effective extension will be vital for the sustainable use of MS, protecting people and the environment, and especially for the adoption of alternative management methods. R&D is required to fill knowledge gaps for example in relation to disease complexes, disease risk prediction and production economics. This report discusses extension and R&D needs and recommends priorities.

Technical Summary

Introduction

Metham (or Metam) Sodium is an organosulphur compound (sodium salt of methyl dithiocarbamate), which is used as a soil fumigant, pesticide, herbicide, and fungicide. It finds application particularly in Western Australian (WA) export carrot production areas, in greenhouses and other intensive crops such as field-grown broccoli, capsicums and lettuce.

The longevity of Metham Sodium (MS) is not certain for a number of reasons. Potential pressures from export markets and enhanced biodegradation rendering the product ineffective are the main issues for growers. The environmental and human toxicity of MS are additional good reasons to look for effective, commercially viable alternative/s.

A desktop review and consultation with growers, advisers and researchers was undertaken to investigate viable alternatives to MS and make recommendations on how to reduce the reliance on MS, especially in the carrot industry.

Findings

Reviews of chemical soil fumigants in other regions (e.g. Canada and the US) have lead to a tightening of regulations and the development of resources/tools for users to improve the safe use of MS. In Europe, while MS can still be sold, its general use is to be phased out by December 2014.

Chemical alternatives to MS are limited. Few alternative broad-spectrum fumigants are registered and they are not considered to be viable substitutes because of their toxicity. **Biopesticides** could successfully replace MS but none are currently available in Australia. **Biological control** (e.g. organic soil amendments) can be used in integrated systems against soilborne diseases that are controlled by MS. **Biofumigation crops**, especially newer brassica and rocket varieties appear to be the most promising replacement for MS. If used correctly, they have the potential to control the same disease spectrum as MS, while providing additional benefits (e.g. reduced tillage, lower pesticide, fertiliser and water use). **Solarisation** and **soil steaming** are not considered good alternatives to MS due to their high costs and lack of overall environmental benefits (excessive use of plastic or energy). **Hydroponics** is considered the most viable alternative to MS in greenhouse production systems.

Integrated Crop Protection (ICP) is part of long-term sustainable production. Together with the MS alternatives above, site selection, rotation and overall crop and soil management, especially nutrition/pH and irrigation management as well as farm hygiene, are essential to controlling diseases.

Costs and benefits of alternatives to MS have to be calculated for individual situations (and depend on the knowledge, skills and attitudes of those developing and using them). **A direct 'drop-in' solution** for MS replacement currently does not exist. **An economic analysis tool** prepared for a previous project (VG12048) can be used to better compare costs and benefits of different options. However, this tool still only compares these on an annual basis, while many benefits relating to soil condition will be cumulative. Environmental and human health costs also remain unaccounted for.

Research, Development and Extension needs are discussed in the report. The recommendations suggest how to reduce reliance on MS and foster the uptake of alternatives.

Recommendations

Extension needs to focus on:

1. Improving the safe use of Metham Sodium using existing resources and tools from Australia and overseas, and available, effective extension pathways
2. Improving site-specific management capabilities for soil and crop health through improving the understanding of integrated management (ICP) options of growers and their advisers; this should be done via applying the large amount of plant and soil health research that has been conducted for the vegetable industry, and relevant information from other industries (e.g. GRDC, Cotton), in Australia, and applicable overseas information
3. Local demonstration trials and practical training targeting regional needs
4. Integrating economic aspects with extension of all technical information, and
5. Linking in with current extension programs in the area of soils, ICP and sustainable production (e.g. EnviroVeg).

R&D needs to focus on:

1. Registration of alternative pesticides (which may come from collaboration with chemical manufacturers) with a lower environmental and human health impact (than MS) that are registered in other countries e.g. US and Germany for the control of soilborne diseases or as fumigants (discussed as alternatives in this report)
2. Access to and / or development and registration of biocide products
3. Biocontrol technologies; especially the integration into vegetable production systems
4. Developing diagnostic tools (e.g. DNA testing) that allow growers to understand risks of marketable yield losses due to specific pests and diseases, which they usually aim to control with MS in an 'all-in-one' approach
5. Identifying where MS is subjected to enhanced biodegradation or resistance so that growers do not waste money on ineffective treatments, focus on where MS is used frequently
6. Understanding disease complexes especially their development and impact, including thresholds, in intensifying production systems
7. Applied R&D on the practical use of integrated methods, especially biofumigation, in major vegetable production systems that currently rely on MS; this must build on previous work and include economic assessments of alternatives (business implications) with due consideration of longer term and triple bottom line costs and benefits
8. Participatory, applied R&D (involvement of growers and their advisers) and extension of practical results and related economic information throughout R&D projects
9. Improving data collection on pest and disease issues so that RD&E can be directed towards issues with the greatest economic impact
10. Updating the economic analysis tool from VG12048 so that longer-term cost and benefits can be estimated
11. Understanding the real cost of the impact on the environment and human health from continued use of MS.

Executive Summary

The issue

Metham (or Metam) Sodium is an organosulphur compound (sodium salt of methyl dithiocarbamate), which is used as a soil fumigant, pesticide, herbicide, and fungicide. It finds application particularly in Western Australian (WA) export carrot production areas, in greenhouses and other intensive crops such as field-grown broccoli, capsicums and lettuce.

Major drivers for continued MS use are the broad pest and disease control spectrum, which makes it a straightforward, economic approach and allows intensification of production systems i.e. short rotations or rotating crops that may host a similar disease range. MS also has a 'cosmetic effect' on root vegetables e.g. 'lustrous' carrots, which appear to be preferred by consumers.

MS has been reviewed by APVMA in 1997 and currently there are no plans to repeat this exercise. State regulations that affect the use of MS presently differ from state to state but none restrict its frequent use.

Still, the longevity of Metham Sodium (MS) is not certain for a number of reasons. Potential pressures from export markets and enhanced biodegradation rendering the product ineffective are the main issues for growers. The environmental and human toxicity of MS are additional good reasons to look for effective, commercially viable alternative/s. An emphasis has to be on providing alternative management strategies to overcome the increasingly limited chemical options available to growers.

The bigger picture

The continued reliance on chemical soil fumigants such as Metham Sodium (MS) can largely be attributed to consumer demand for low cost, good quality, nice-looking vegetables. This drives the need for intensification and specialisation in the vegetable industry to maintain economical viability. Ironically, consumer expectations and market requirements may also affect the continued acceptability of using 'old style' broad-spectrum fumigants even if the products are not deregistered.

Unfortunately, intensification has, in many cases, changed soil conditions and reduced inherent disease suppressive soil properties, thus reinforcing a reliance on fumigation to deal with soilborne diseases, pests and weeds. Much stated drivers for continued MS use, besides the need for 'attractive', inexpensive vegetables, are its apparent broad-spectrum efficacy and low cost.

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In addition, MS can be subject to enhanced biodegradation with specialist microbes able to inactivate it quickly. Many growers are aware of this risk but do not know whether they are affected.

Replacing a broad-spectrum fumigant with integrated methods requires growers and their advisers to understand the complexity and risk profiles of all pests and diseases that may affect their crops. Integrated solutions are not simple 'drop-in' replacements. These need to be site-specific and adjusted to individual farm circumstances and growers' personal preferences. This often takes time. The economics of most MS alternatives require looking at cost / benefits over longer timeframes and use of more complex calculations than those for annual crop gross margins. Economic survival however is often a year-to-year issue for vegetable producers; this prevents many from taking a longer-term view.

Approach

A desktop review and consultation with growers, advisers and researchers was undertaken to investigate viable alternatives to MS and make recommendations on how to reduce the reliance on MS, especially in the carrot industry.

Chemical alternatives to Metham Sodium

Some chemical fumigant alternatives to MS are registered in Australia e.g. Telone (1,3-D) and Telone C35 (1,3-D and Chloropicrin), which offer a similar level of effectiveness, yet are more costly and present their own suite of problems such as environmental impacts and enhanced biodegradation issues similar to MS. They are also ‘old style’ chemicals and thus do not offer a suitable long-term alternative for growers. Additional chemical fumigants registered in other countries have been tried here. They are also toxic to humans and the environment; thus they do not offer a viable alternative.

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Recommendations

Extension needs to focus on:

1. Improving the safe use of Metham Sodium using existing resources and tools from Australia and overseas, and available, effective extension pathways
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Glossary of Terms and Abbreviations

Term	Meaning
APVMA	Australian Pesticides and Veterinary Medicines Authority
EDN	Ethanedinitrile
Enhanced biodegradation	Conversion or breakdown of the chemical structure of a pesticide catalysed by bacteria or other biological means (enzymes), resulting in loss of biological activity
EU	European Union
Fumigation	The process of applying a pesticide in the gaseous phase, including the use of liquids that evaporate, or solids that sublime, burn or react, to produce a gas.
GM	Gross Margin
HAL	Horticulture Australia Limited
ICP	Integrated crop protection
MB	Methyl Bromide
MS	Metham Sodium (Australian spelling) Metam Sodium (US and EU spelling)
MSDS	Material Safety Data Sheet
Pesticide resistance	Development of tolerance to a pesticide by a target population, generally through natural selection boosted by repeated use of the same active ingredient
US	United States

1 Introduction

Metham (or Metam) Sodium (MS) is an organosulphur compound (sodium salt of methyl dithiocarbamate), which is used as a soil fumigant, pesticide, herbicide, and fungicide. MS can be prepared from methylamine, carbon disulfide, and sodium hydroxide; or from methyl isothiocyanate and sodium thiolate.

MS as a soil fumigant is used to control nematodes, symphylids soil-inhabiting insects, germinating seeds of weeds, soil fungi and other soilborne pests. It is generally used as a remedy for severely diseased sites or for seedbed preparation, especially when a suitable rotation does not occur.

MS finds application particularly in Western Australian (WA) export carrot production areas, in greenhouses and other intensive crops such as field grown brassicas, capsicums and lettuce. Under perfect operating conditions, MS's broad spectrum and long lasting effects have made MS a product of choice. Other methods are not proven to offer a cost effective alternative for adequate control of target organisms, and managing associated risks of marketable yield losses.

Products containing MS first became available in the 1950's. At the present time, MS is manufactured by numerous companies in many countries and sold under several names to Australian growers. The primary breakdown product of MS, via a rapid abiotic decomposition process in soils, is methyl isothiocyanate (MITC). This active agent has a high general toxicity, including to beneficial soil organisms. It has good transportability in the soil, and a great potential for volatilisation. It has a high Environmental Impact Quotient (EIQ: http://www.nysipm.cornell.edu/publications/EIQ/), so that its routine use cannot be part of an Integrated Pest Management (IPM) or Integrated Crop Protection (ICP) approach.

MS products are frequently applied in irrigation water or followed by irrigation to move it through the rootzone. Research has shown that it is possible to move MS through the root zone faster than it is able to convert to the active MITC. Thus ineffective control in upper soil layers can occur. Growers cannot be certain when this happens and, given the additional environmental and human safety risks, an alternative, effective management of target organisms and associated risks is desirable.

Over the past 15 years, enhanced biodegradation of the active MITC has increasingly been reported in international scientific publications. One of the reasons for this issue was the increased use of MS after the use of the soil fumigant Methyl Bromide was prohibited or restricted. Other issues driving the use of MS are increasingly intensified production systems and consumer demands for high quality produce.

CSIRO researchers investigated WA soils and identified increasing biodegradation problems with repeated use of the product. An increased soil pH due to the use of lime (Warton & Matthiessen 2005) and the proliferation of specialised soil microorganisms using MITC as a food source were found to be involved in the problem in WA.

Therefore, along with many other older pesticide products, the longevity of MS is not certain, and effective, commercially viable alternative/s need to be introduced. The emphasis has to be on providing alternative management strategies to overcome the increasingly limited chemical options available to growers.

2 Methodology

2.1 Desktop review

A desktop review was undertaken to investigate viable alternatives to MS. This included:

- Reviewing international research on methyl bromide (MB) alternatives; MB provides similar soil sterilant action to MS and has been banned for some time in many countries, leading to the development of alternatives and their successful use on farms
- Reviewing information about alternative preventative and control methods of MS target organisms, including crop genetics, from Australian and overseas research, their fit with target crops, production systems, regions, soils and climates. This also involved identifying the adoption potential and adaptation or R&D needs of alternatives and collating together with MB alternatives
- Reviewing available and 'in development' risk management options such as soil DNA testing
- Investigating how other industries (e.g. nursery, fruit) deal with MS and potential alternatives
- Collating available data on MS use by crop and target organism.

2.2 Consultation

The primary purpose of the consultation was to understand:

- Drivers for MS use (economic, operational, market)
- Drivers for needing MS replacement including efficacy, pest, weed and disease profiles by crop
- Requirements of any potential alternatives (cost, fit with rotation, equipment, reliability)
- Any relevant new product developments by crop protection producers and what they recommend
- Confirmation of other industries (nursery, fruit) that deal with MS and potential alternatives
- Whether APVMA has any plans in regards to an MS review
- What alternatives have been used or are proposed by European and USA industry bodies, extension services and agricultural departments.

Consultation comprised informal phone conversations or meetings with growers, agronomist, researchers, MS producers and resellers, and an APVMA representative. In total, there were 16 consultation participants.

3 The current situation in Australia

3.1 Metham Sodium (MS) use

At the present time, MS is manufactured by numerous companies around the world and sold under several names to Australian growers and contractors (refer to www.**apvma**.gov.au). MS is registered in Australia in several end use products (EUPs) as non-residual pre-planting treatments, for the control of weeds, nematodes, symphylids (except in Tasmania), fungi, soil insects and other soilborne pests in ornamentals, tobacco food and fiber crops. MS is also registered as an inhibitor of root growth in sewer lines for use by plumbers, drainers and sanitary engineers (APVMA 1997).

In 1997, the Australian Pesticides and Veterinary Medicines Authority (APVMA), formerly the National Registration Authority (NRA), reviewed the use and regulation of MS, dazomet and MITC in response to occupational and public exposure concerns. Box 1 outlines the main recommendations of the review.

Box 1: Recommendations of the 1997 APVMA review of MS, Dazomet and MITC

I. Changing the labels on products containing MS and dazomet to include appropriate warnings and precautions.

II. Strengthening safety directions and information on MS and dazomet product labels for personal protective equipment (PPE), re-entry/re-handling periods and minimisation of vapour escape in treated soil.

III. Revising product labels to include statements specifically prohibiting the discontinued methods of application to ensure they are not allowed under any State control of use regimes.

IV. Material Safety Data Sheets (MSDS) for all products must be submitted for assessment as a condition of registration.

V. Restricting products to uses which would not present a risk to human health. For example:

- MS must not be applied in high wind, temperatures over 32˚C, to dry soil, or in conditions of low humidity
- MS must not be used by hand or by directed spraying (including sprinkler can), in overhead sprinkler systems, in treating potting soil by the loose mixed method or via shredder, or by flood irrigation.

MS labels and MSDSs for registered products are available from the APVMA website (www.**apvma**.gov.au). They demonstrate the variability of how information about the product, its safety and its applications is conveyed to MS users. MS labels are generally compliant with the APVMA recommendations (Box 1). They outline in a generic fashion:

- Storage directions
- Safety directions (including PPE)
- First aid procedures

- Directions for use - including precautions, prohibited uses, applications and re-entry periods
- Protection of natural environments and other crops.

Only the All Fire label does not provide this basic level of detail.

3.1.1 Regulated use of MS across Australian states

MS suppliers estimate that the Australian Metham market is around 4.5 million litres annually. Working on an average use rate of 300L/ha about 15,000 hectares are treated each year. This includes fruit, vegetable and nursery crops.

There is disparity in the regulated use of MS across Australian states. Table 3-1 provides regulatory details, as they are available on departmental websites.

Table 3-1: Requirements for agricultural chemical use applicable to MS

State or Territory	Requirements for agricultural chemical use
New South Wales	The following chemicals are classified as a fumigant in NSW: ▪ Methyl bromide ▪ Phosphine ▪ Ethylene oxide (except single dose canisters) ▪ Ethylene dichloride ▪ Carbon disulphide ▪ Chloropicrin ▪ Hydrogen cyanide. A certificate of competency is required for the use of the above fumigants. MS or its primary breakdown product and active methyl isothiocyanate (MITC) are not listed as a fumigant in NSW; therefore a certificate of competency is required for its use. All users of restricted chemicals must be trained to at least AQF level 2 standard, and AQF level 3 if work is to be undertaken without supervision. There is no specific requirement for the use of MS.
Northern Territory	Users of Schedule 7 (Dangerous Poisons) and restricted chemicals registered by APVMA require training and authorisation from the Department of Resources. There is no specific requirement for MS use. If applying chemicals for a fee e.g. as a contractor, the user must be licensed by the Department of Resources.
Queensland	A commercial operators license is required for people who are distributing herbicides (spray, spread or disperse) using ground equipment (any machine or apparatus other than an aircraft) on land that they do not own or occupy. There is no specific requirement for the use of MS.
South Australia	A prescribed chemical training course is required to be undertaken by anyone who is using, buying, handling, storing or transporting S7 Chemicals. There is no specific requirement for the use of MS.

State or Territory	Requirements for agricultural chemical use
Tasmania	A prescribed chemical training course is required to be undertaken by anyone who is using, buying, handling, storing or transporting S7 Chemicals. There is no specific requirement for the use of MS.
Victoria	Agricultural Chemical Users Permit (ACUP) introduced in 1996 to restrict high-risk chemical use to people who are appropriately trained. The ACUP is a 10-year permit that authorises the holder to purchase and use 'restricted supply' chemicals. In Victoria MS is 'restricted use' chemical and therefore an ACUP is required.
Western Australia	If applying chemicals for a fee e.g. as a contractor, then users must be licensed by the WA Department of Health. There does not appear to be any restrictions or requirements of users applying MS to their own property.

Following the 2008 Productivity Commission report on the regulation of chemicals and plastics, the Council of Australian Governments (COAG) directed the Primary Industries Ministerial Council (now the Standing Council on Primary Industries [SCoPI]) to develop a single national framework to improve the efficiency and effectiveness of the regulation of agricultural chemicals and veterinary medicines (agvet chemicals).

The changes proposed by the Department of Agriculture via the national framework will need to be actioned by the states and territories[1] via changes to state and territory control–of–use legislation. The proposed framework only outlines the general Access to Agricultural Chemicals model. Further details of these models will be determined during the reforms' implementation phases.

These reforms aim to address current variations in states and territory regulation, relating to:

- Licensing and competency requirements for chemical users and fee–for–service users
- Limited and inconsistent monitoring of chemical residues, including varying levels of integration with state, federal and private sector monitoring systems
- Variation in access to chemicals restrictions, including off–label use restrictions and application of additional chemical controls
- Compliance and enforcement of chemical use in accordance with registered and other permissible uses
- Record–keeping requirements for chemical use.

The regulatory model published on the federal Department of Agriculture website[2] suggests minimum harmonised requirements (relevant excerpt below):

- All fee–for–service providers (e.g. pest controllers, ground and aerial applicators, sheep dippers) are required to be licensed, both the fee–for–service businesses and individuals within those businesses are required to be licensed

[1] The commonwealth only regulates pesticide chemicals up to the point of retail sale. All control of use is managed by the individual state or territory.
[2] http://www.daff.gov.au/agriculture-food/ag-vet-chemicals/domestic-policy/history-of-coag-reforms/regulatory-model

- Licensing will not be required for users of Restricted Chemical Products (RCPs) and Schedule 7 (S7) chemicals who are not operating a fee–for–service business (general users, including farmers), except when specifically required due to regional need.

In addition to the proposed licensing model, the following proposed harmonised minimum training requirements are included:

- All fee–for–service providers (e.g. pest controllers, ground and aerial applicators, sheep dippers) are required to hold, as a minimum, Australian Qualifications Framework (AQF) Level 3 competency determined to be appropriate for the occupation as a condition of licence
- All users of RCPs and S7 chemicals are required to hold, as a minimum, AQF Level 3 competencies determined to be appropriate for the use of the product (but with no licensing requirement). Although these users will not require licenses, they will still be required to maintain records of chemical use.

This means that under the national framework anybody who does not operate a fee for service business has access to MS and other fumigants without the need for a licence as long as appropriate training is completed.

3.1.2 MS in Australian carrot production systems

MS use in the carrot industry is a focus of this study. The reason for this is that carrot production, especially in Western Australia (WA) but also in parts of Queensland heavily rely on MS use to maintain product quality in intensive production systems. WA, the largest carrot producer by state, also dominates exports and has the opportunity to expand to new SE Asian markets, if trade negotiations continue to be successful and market access conditions can be met. Pesticide use and especially MS may potentially become an issue for access to some new markets.

The carrot industry

Total Australian production is around 300,000 t and the domestic market is well supplied throughout the year. At the moment, the carrot industry in Australia is reasonably consolidated with approximately a half dozen large-scale suppliers dominating the industry, especially exports. Several medium sized producers mainly supply the domestic market or access export markets through merchants. The consolidated nature of the industry means that prices tend to be relatively stable. The industry is underpinned by supply contracts to the major supermarket chains and this as well as the relationship between scale and efficiency (cost of production) has driven consolidation.

Summer/Autumn production is dominated by Tasmania whilst Queensland supplies winter production. Western Australia (WA) can produce carrots all year round although the quality tends to suffer in the summer months due to heat. As a consequence, one of the major WA exporters is now producing carrots in Tasmania to service its customers during summer. There is considerable interaction between major producers and counter seasonal supply arrangements exist e.g. between Tasmanian and Queensland based companies to supply key overseas and markets all year round. Most of the major carrot-producing companies export, with SE Asia, Asia and the Middle East the prime markets. WA enjoys a competitive advantage due to its proximity to the Middle East and Asia. Shipping time from Fremantle is only around seven days to Singapore and Hong Kong.

MS use

Across Australia, the use of MS in carrot production varies considerably, predominately in response to soil type and rotation practices. In Tasmania for example, chemical soil fumigants are not used. There, carrots are produced in Ferrosol soils (clay loam), generally have one early fertiliser application and are irrigated once or twice a week in summer (Pung et al. 2003). Carrots are typically sown at intervals of at least three years in rotation with a range of other vegetable, seed, grain and industrial crops (poppies, pyrethrum) or pastures. Similarly, in Victoria and NSW, carrot crops are generally produced with relatively low inputs compared to other vegetable crops, and in most cases without soil fumigation (Pung et al. 2003, Kourmouzis, pers. comms 2014, Hendrichson pers. comms 2014). The main pest and disease control measures are rotation and the use of biofumigation crops. On lighter soils in South Australia, irrigation and fertilisers are applied regularly through centre pivots to match crop needs. Fallow and biofumigation crops are used to break disease cycles and avoid fumigation (Kourmouzis, pers. comms 2014).

Horticulture Australia Limited (HAL) project VG95010 - Carrot export development (cont'd VG510) was conducted in 1997-98. The project investigated integrated management of cavity spot disease in WA carrots grown on coarse, sandy soils and irrigation management. The project identified carrot variety, time of sowing and control by two chemicals, the soil fumigant metham sodium, and the oomycete-specific fungicide metalaxyl (Ridomil®) as ways to reduce *Pythium* diseases such as cavity spot. It determined that irrigation system uniformity was a key to ensuring good, predictable crop growth. Advice to growers included investigating irrigation system redesign, pump maintenance, shift area, valve replacement, windbreaks, and change of sprinkler or jet modification.

MS soil fumigation prior to sowing remains the common practice in Western Australia (WA) carrot production. They are grown intensively without other crops in the rotation and growers believe that MS alternatives are too expensive, unreliable and challenging to use. The intensive specialised production on sandy soils with little or no organic matter, requiring regular weekly fertiliser applications and daily irrigation in summer, are given as a reason for needing a reliable, efficient, broad-spectrum fumigant. Economic and market pressures are main drivers of production intensity and specialisation.

Box 2: The use of MS in Queensland carrot production

Carrot growers in Queensland are using MS mainly to control Pythium spp. and other soilborne diseases and weeds. They feel that MS additionally provides a 'nice finish' to the carrot roots. However, many growers have been trying to replace MS in the past 2-3 years. While the broad spectrum pest and disease control delivered by the product is welcome, its use is considered 'unpleasant'. Growers have to apply MS about 3 weeks prior to sowing carrots. Wet autumn weather in recent years forced them onto their land with the heavy fumigation machinery when it was still too wet. This caused compaction, which not only affected the carrot crop but also subsequent rotational crops. Therefore many producers (estimated up to 50%) tried alternative treatments and have decided to 'wean themselves off' the reliance on MS. One of the main alternatives is the use of biofumigants. Even though less effective than MS in many cases and more expensive on a comparison of 'treatment' costs alone, they have been chosen for the added longer-term benefits of maintaining soil organic matter.

3.1.3 MS in other Australian vegetable production systems

In addition to carrots, MS is commonly used in the following main vegetable crops:

- Brassicas
- Lettuce and other leafy vegetables
- Capsicums
- Potatoes (not covered by the vegetable levy)
- Tomatoes (not covered by the vegetable levy).

MS may be used from time to time to control soilborne pests and disease in other vegetable crops (celery, beans, peas, beetroot, cucurbits). It is also routinely used in greenhouse production.

Box 3: The use of MS in Victorian vegetable production

Growers in the Werribee vegetable production region of Victoria are using MS mainly to control Clubroot in cauliflower and broccoli crops. Growers indicated there are few alternatives that provide the same broad-spectrum efficacy and affordability as MS. In the Werribee vegetable production systems, MS is generally applied every 2 or 3 years prior to sowing of cauliflower or broccoli crops. The crops are rotated with lettuce in summer and celery in winter, which also reduces the risk of disease. MS is injected directly into the soil during warmer weather. Some growers have used the fertiliser Perlka as an alternative, however its application is required more frequently making it less cost-effective and it has a narrower spectrum than MS. In the Werribee region, MS continues to be applied as a "safeguard" mechanism to reduce the risk of potential soil borne disease.

3.2 Drivers for MS use in Australia

Affordability, ease-of-application and apparent effectiveness in the control of nematodes, soil borne diseases and weeds are among the key drivers mentioned for the continued use of MS, particularly in intensive production systems.

3.2.1 Effectiveness

On one hand…

The effectiveness of MS in controlling a wide range of soilborne pathogens, pests and weeds is widely documented over and above the efficacy trials that allowed for registration of the active ingredient (Slusarski et al. 2012; Martin 2003; Stephens et. al. 1999). Field trials in the application of MS and other MITC generator substances, such as dazomet, on multiple crops in the EU e.g. tomatoes, strawberries and peppers, consistently resulted in increased yields and reduced competition from pests and disease (Slusarski et al. 2012).

Many of the soil-based pathogens that affect carrot crops and other vegetables (see Table 3-2 and Table 3-3) are treated effectively by soil fumigants such as MS. For example, Fusarium, Pythium and Rhizoctonia as disease 'complexes' are becoming increasingly important soilborne disease concerns in vegetables; they are particularly difficult to control due to the scarcity of effective fungicides and complexity of disease issues (Dal Santo & Holding 2009), hence reliance on MS remains high.

On the other hand…

Despite MS proving effective in most cases of pest and disease management, it's sustained efficacy under continuous use is uncertain due to issues associated with enhanced biodegradation and it's ability to rapidly move through the upper layers of the soil without the desired effect on pests and diseases in the rootzone (refer to Section 3.3.).

If carrot seed carries diseases the use of MS may allow these diseases to thrive due to a lack of antagonists in the soil unless the disease is controlled via effective seed dressing.

Table 3-2: The main diseases impacting carrot crops that are controlled by MS

Disease	Description
Sclerotinia spp. (*S. sclerotiorum* and *S. minor*)	▪ Favoured by high soil moisture and dense canopy ▪ Spores are spread by wind and rain, generally in summer ▪ Symptoms include a water soaked lesion at the base of the foliage and die back of foliage. Infection can also include cottony white mycelia growth on the carrots and crop residue. ▪ In storage the white mycelium of the pathogen grows rapidly and infects carrots over large areas (Bisht & Gonsalves date n/a)
Fusarium spp. (*F. oxysporum* and *F. solani*)	▪ Cause damping off and root rot ▪ Can cause “damping off” in some crops ▪ Can remain in the soil for long periods of time ▪ Infections can be spread on ‘root’ vegetables and seed contaminated with dust or trash (Dal Santo & Holding 2009).
Pythium spp. Root dieback, forking, cavity spot, brown rot	▪ Commonly referred to as “damping off” ▪ Water loving fungus – problematic in waterlogged conditions ▪ Most damaging at seed and seedling stage ▪ When attacked, seeds fail to germinate and eventually disintegrate ▪ Infection of established plants can cause root rot ▪ Causes cavity spot in carrots and causes them to fork (Dal Santo & Holding 2009).
Rhizoctonia spp. Crown rot, crater rot (cavity spot)	▪ Attacks emerging and mature crops and can cause post harvest losses ▪ Causes crater rot in carrots ▪ The majority of root rots are caused by *Rhizoctonia solani*
Sclerotium rolfsii	▪ Attacks roots in warm climates, can cause damping off ▪ The first visible symptoms are progressive yellowing and wilting of the leaves ▪ Invaded tissues are pale brown and soft, but not watery ▪ Has a very wide host range, including may vegetable crops
Alternaria radicinia Black rot	▪ Causes damping off and poor establishment ▪ Black rings of decay develop around the base of the stem ▪ Usually seed borne but survives on crop residues and microsclerotia can stay in soil for up to eight years
Phythophtora spp.	▪ Attacks emerging (damping off) and mature crops and can cause post harvest losses
Nematodes	▪ Both *Meloidogyne* spp. (root knot nematode) and *Pratylenchus* spp. (root lesion nematode) cause damage to carrot crops ▪ Juvenile root knot nematodes move into the roots, creating permanent feeding sites. This leads to the development of root galls. Symptoms are similar to those caused by *Fusarium, Pythium* and *Rhizoctonia.* Causes pack-out of carrot crops due to forking and distortion (Davison & McKay 2013; Hay et. al. 2013) ▪ Damage caused by nematodes can allow *Fusarium* (as well as other damping off fungi e.g. *Rhizoctonia*, *Pythium*, *Phythophtora*) to cause further damage

Table 3-3: Main target organisms for MS in other major vegetable crops

Crop	Main target organisms
Lettuce	*Rhizoctonia solani*, Thievaiopsis basicola, *Sclerotinia sclertiorum* and *S. minor*, *Sclerotium rolfsii, Pythium* spp.
Broccoli and other brassicas	*Plasmodiophora brassicae* (Clubroot), Stem canker diseases (*Rhizoctonia* spp. *Leptosphaeria maculans*, *Phoma* spp, *Fusarium* spp, *Sclerotinia* spp, *Pythium* spp)
Capsicum	*Fusarium oxysporum, other Fusarium* spp. *Pythium* spp.

3.2.2 Controlling risks in intensive production systems

The problems MS is used to address e.g. weeds, nematodes and chronic soil borne disease, are exacerbated by short rotations or back-to-back production of the same crop.

For example, WA carrot production systems are highly mechanised, intensive production systems that are producing nearly all year round. As one industry representative explained, carrot production systems are moving towards large-scale monocultures, which makes managing soil disease, weeds and pests a challenge. Compared to other carrot growing regions in Australia e.g. Tasmania, where rotations are usually wide[3] and rotational crops such as broccoli, grains, poppies, pastures and green crops are grown to better manage soil disease and pests, in WA, rotation options are limited by the availability of suitable land, sandy soils, profitable alternative crops and the current irrigation infrastructure.

Growers, who are operating intensive production systems and use MS, feel that there is a scarcity of alternative controls that offer the same level of disease and pest control as MS. According to WA carrot growers, the uptake of non-chemical management strategies, such as rotational and/or biofumigation crops, has been restricted in carrot production systems due to light soils (which they feel are not well suited to longer rotations with alternative crops) as well as the low profitability and lack of markets for other crops.

Growers relying on MS for carrot production in Queensland raised similar issues relating to specialisation and intensive systems. Besides the lack of markets, producing a range of crops for rotation purposes would mean additional investments in infrastructure and equipment to handle these crops. Thus, the reliance of fumigation is considered to be high in order to sustain back-to-back crops, short rotations and persistent pathogens.

Brassica, capsicum and greenhouse vegetable producers similarly mentioned a lack of market opportunities and economic pressures as a reason for close rotations (<3 years) or back-to-back production of crops and the necessity to fumigate to sustain the intensity and viability of production. Capsicums, like carrots, are grown in highly intensified production systems, which rely on soil fumigation to manage soil borne disease. A study undertaken by Pung et al. (2003) reported an inverse relationship between soil health and plant health in capsicum crops in Queensland. The weight of marketable fruit, which is considered a measure of crop health, was not correlated with soil health indicators such as bacterial-feeding nematodes, C_1 and mycorrhizae. It was concluded that soil health and plant health

[3] Where crops from the same type (e.g. brassicas) are ideally grown more than four years apart

can be unrelated e.g. fumigation can increase marketable yield (plant health) at the expense of soil health in an intensely grown crop such as capsicum.

The same study on carrot crops in Tasmania found that marketable yield was increased by wide rotations and especially when pasture breaks were included i.e. soil and plant health were correlated. The study suggests that if soil health conditions are compromised due to intensive production of the same crop on the same land, fumigation can be a reliable tool to achieving high marketable yields. The study did not include investigating the long-term sustainability of the practice. It is possible that intensification under MS use can lead to a decline of soil structure/compaction, which ultimately will affect irrigation and nutrition management and thus yield potential.

Tasmania is in a unique situation with most crops being produced under contract for processors, packers and seed companies. Planting, harvesting and other crop management operations are performed by contractors with specialised equipment. This allows growers to maintain long rotations. Most vegetable growers have livestock so pasture breaks are possible to rest the soil without loss of income and rotational crops such as grain or seed crops can be grazed to improve returns.

Fumigants have allowed specialisation and intensification of vegetable production systems in response to market and price pressures. The prolonged use of and dependence on MS now makes it difficult for growers to break the cycle of chemical fumigation and introduce alternatives, especially if the alternatives are more complex, expensive, and potentially less reliable in the short term.

Box 4: Understanding of pests and disease risks and potential product failure in intensive production systems

Even though issues such as enhanced biodegradation and potential movement of the active ingredient with water out of the rootzone raise uncertainty around unfailing reliability of MS (see Section 5.1.3), grower confidence in the MS remains high. Especially amongst growers in WA there is a strong perception that “it’s too risky to grow carrots without MS”. Broader discussions with vegetable growers elsewhere confirm that MS continues to be applied by many as a “security blanket” to control unspecified risks posed by pathogens and weeds. Information on actual threats from target disease and pest species is not the basis for decision-making on MS use. One reason for this is that adequate soil testing methods are not routinely available to growers. Testing for enhanced biodegradation is not available as routine tests.

3.2.3 Ease of application

With the right equipment MS can be efficiently incorporated into the soil. It is water-soluble so it can be applied through a drip irrigation system. In spite of this, many growers do not like to handle Metham Sodium based on the need for specific machinery and potential OH&S issues. MS application via spray irrigation is prohibited (refer to Box 1).

Figure 3-1: An applicator used to inject Metham Sodium into the soil at a farm at Werribee, Victoria

3.2.4 Cost of production

In intensive production systems MS is considered the most economically viable pest and disease control mechanism. Feedback from growers was that MS could help achieve uniform establishment and early consistent crop maturity; achieving maximum early seasonal yields can increase economic returns. The lack of alternatives that provide comparable control of a range of diseases and pests, and are considered equally economical is driving the continued use of MS (see Box 5). Many of the alternatives to MS that have been trialled in high-return crops such as strawberries, are not considered viable options by growers of carrots or other vegetables due to the low margins of these crops.

Box 5: Feedback on the economic feasibility of MS vs. a non chemical alternative

Discussions with WA carrot growers and industry representatives suggested the cost of MS alternatives, such as mustards as a biofumigant, is prohibitive. On average biofumigants cost approximately $900/ha, with uncertain or low effectiveness, compared with approximately $500/ha for MS. There remains a general feeling that it is “too risky to grow carrots without MS”.

4 The situation for chemical soil fumigants in other regions

In the past, soil fumigants, such as MS and methyl bromide have had widespread application in Europe and the United States. This has been due to their effectiveness in reducing damage caused by soil borne fungi and nematodes. Methyl bromide use has been banned in these countries for some time and its replacement of choice, MS, is either gradually phased out or has been heavily regulated in recent years.

4.1 Fumigants in North America

4.1.1 Methyl Bromide (MB) in the United States

MB is an odorless and colorless gas used broadly in agriculture to manage soil pests. It's popularity was primarily due to the broad spectrum pest control it provides, its high vapor pressure facilitating distribution through the soil profile, cost-effectiveness, and comparatively short plant-back intervals (Martin 2003).

At the beginning of 2005, MB was phased out in the United States in accordance with the Montreal Protocol on Substances that Deplete the Ozone Layer (Protocol)[4] and the U.S. Clean Air Act. The phase out began in 1993, when MB was classified as a class 1 stratospheric ozone-depleting substance (Martin 2003). The U.S. EPA has now labeled MB as a Restricted Use Pesticide, due to acute toxicity.

While use of MB is prohibited, there are some critical use exemptions (CUE) in circumstances where there are no viable alternatives and market disruptions may result. A provision of this exemption is that the applicants reduce emissions by technologically and economically feasible steps as well as continue to aggressively search for MB replacements (Martin 2003). Reapplication of an exemption is required annually and will expire in 2015.

The CUE has allowed limited use of MB on California strawberry farms. The strawberry industry also substitutes MB with the fumigants chloropicrin, 1,3-dichloropropene (1,3-D), and MS (CDPR 2013). Examples of chloropicrin and 1,3-D use are discussed in Section 5.1.

4.1.2 Metham Sodium (MS) in the United States

MS was one of the most widely used pesticides in the United States, with approximately 30 million kilograms used in 2001[5]. Its use increased with the ban on Methyl Bromide (MB) effective from 2005. Interestingly, early MB replacement trials with MS reported inconsistent results[6]. MS still became the most frequently used replacement option. In 2006, MS was named the third most widely used pesticide in U.S. agriculture.

The United States Environmental Protection Agency (USEPA) instituted new requirements for soil fumigation products including metham sodium and metham potassium effective from September 24, 2013. The goal of the new regulations is to protect workers and bystanders while maintaining the benefits of the products for agricultural production.

[4] United Nations Environment Programme (UNEP) (1999) The Montreal Protocol on substances that deplete the ozone layer as adjusted and amended in London 1990, Copenhagen 1992, Vienna 1995, Montreal 1997, Beijing 1999

[5] 2000-2001 Pesticide Market Estimates, U.S. Environmental Protection Agency

[6] Nelson S.D. et al. 2004; Efficacy of Metam Sodium Under Drip and Surface Spray Application in Florida Tomato Production. Subtropical Plant Science, 56: 16-20

The US EPA supports users in applying the new regulations through a web-based 'Soil Fumigant Toolbox' which provides training, outreach, and other resource materials for applicators and handlers, communities, state and local agencies, and others interested in understanding and implementing the current requirements for safe use of soil fumigants. http://www.epa.gov/pesticides/reregistration/soil_fumigants/index.htm.

The National Association of State Departments of Agriculture Research Foundation (NASDARF) and the U.S. Environmental Protection Agency (EPA), Office of Pesticide Programs, developed a Fumigation Manual with detailed instructions on the safe and efficient use of fumigants (Methyl Bromide, Methyl Iodide (Iodomethane), Chloropicrin 1,3-Dichloropropene (1,3-D), Dimethyl Disulfide (DMDS), Dazomet and Metham Sodium/Metham Potassium (http://www.novasource.com/english/news/Documents/National%20Fumigation%20Manual-revised-2012.pdf).

4.1.3 Metham Sodium and other soil fumigants in Canada

The Heath Canada Pest Management Regulatory Agency's (PMRA) re-evaluation of the soil fumigant cluster is ongoing. In the meantime the PMRA is requiring label improvements to further limit user exposure and further protect bystanders and the environment. These label improvements are considered a first step in the re-evaluation of the Canadian uses of the products containing these active ingredients.

A key component of the label improvements for soil fumigant products containing chloropicrin, dazomet, metham sodium or metham potassium is the requirement of a Fumigation Management Plan (FMP) for all applications. This is a similar approach to that outlined in the US EPA 'Soil Fumigant Toolbox' which provides FMP templates.

A Fumigation Management Plan is an organised, written description of the required steps involved to help ensure a safe and effective fumigation. It will also assist in complying with pesticide product label requirements. Instructions for the preparation of a Fumigation Management Plan are required to be part of the product label. In addition, a Fumigation Management Plan template will be developed by the PMRA in consultation with registrants in order to help users meet the Fumigation Management Plan requirements. Chemical-specific label improvements are also required for all registered uses. Please refer to Re-evaluation Notes for chloropicrin (REV2012-09 Label Amendments for Soil Fumigants Products Containing Chloropicrin), dazomet (REV2012-10 Label Amendments for Soil Fumigant Products Containing Dazomet), and metham sodium/metham potassium (REV2012-11 Label Amendments for Soil Fumigant Products Containing Metham Sodium of Metham Potassium) for a full description of the required amendments.

The regulatory process for the re-evaluation of antimicrobial products containing chloropicrin, dazomet, metham sodium or metham potassium is communicated in Re-evaluation Note REV2012-07, Chloropicrin, Dazomet, Metham Sodium and Metham Potassium Label Improvements for Antimicrobial Products (http://www.hc-sc.gc.ca/cps-spc/pubs/pest/_decisions/rev2012-07/index-eng.php).

4.2 Metham Sodium in the European Union

In July 2009, the Council of the European Union passed a decision to phase out MS use based on its toxicity to humans and the environment, and the paucity of data relating to these potential impacts. According to the EU Directive 91/414/EEC authorisations for plant protection products containing metham were withdrawn by 13 January 2010.

Despite the ban, “essential use” has been allowed to continue in 15 of the 27 EU Member States where there are no effective alternatives available for the control of harmful organisms (Council of the EU 2009).

Member states having essential use permits (listed in column A of Annex 1 to the EU Directive, see Appendix 1) may maintain authorisations for plant protection products containing metham for the uses listed in that Annex until 31 December 2014, provided that they comply with the following conditions. The member state:

i. Ensures that no harmful effects to human and animal health and no unacceptable influence on the environment are caused;

ii. Ensures that such plant protection products remaining on the market are relabelled in order to match the restricted use conditions;

iii. Imposes all appropriate risk mitigation measures to reduce any possible risks in order to ensure the protection of human and animal health and the environment;

iv. Ensures that alternative products or methods for such uses are being seriously sought, in particular, by means of action plans.

A condition of continued use has been that “alternative products or methods are being seriously sought” and action plans are developed (Council of the EU 2009). There has however, been concern that the 15 Member States still using MS under essential use permits have not taken their responsibilities seriously in developing alternatives. No single Member State of the 15 had started action plans or taken serious steps to develop viable alternatives by 2011 (PAN-Europe 2011).

Based on 2010 data, the heaviest users of MS were France, Spain, the Netherlands, Portugal and Greece (PAN-Europe 2011). The remaining 12 member states including Germany, Austria and Denmark that have stopped using MS have moved to more sustainable alternatives such as Integrated Pest Management (IPM), presenting a strong case against the reliance on chemical fumigants such as MS and 1,3-D, which was also banned by the EU in 2011. IPM/ICP is discussed in more detail in Section 5.2.

A peer review of the EU pesticide risk assessment (required by the EU system) of the active substance Metham was conducted for the European Food Safety Authority and a report submitted in 2011[7]. For the risk assessments representative MS use was soil fumigation prior to the planting of carrot, lettuce, cucumber, aubergine, pepper, potato, strawberry, tomato and grapes. The representative formulated product for the evaluation was “Metham sodium 510 g/L”, a soluble concentrate (SL), registered under different trade names in Europe.

[7]European Food Safety Authority2011; Conclusion on the peer review of the pesticide risk assessment of the active substance metam. EFSA Journal 2011;9(9):2334

It was confirmed that risks were in the main due to the MS breakdown product MITC. Mammalian and aquatic toxicity (mainly due to MITC runoff) were rated high. After the application of the 608.4 kg a.i./ha, there was no clear indication of full recovery of earthworms after one year. The study included the assessment of soil non-target macro-organisms such as *collembola* and *gamasida*. There was no evidence from the results in the test that long-term effects on these soil macro-organisms occurred due to the MS treatment. All affected soil-dwelling invertebrates had recovery in abundance within the same season and no adverse effects extended into the year after the treatment. Therefore the risk of metam-sodium and MITC to soil macro-organisms was considered to be low for all of the representative uses. No effects of >25 % on soil respiration and nitrification were observed in tests with metam-sodium up to a concentration of 608.4 kg a.i./ha. This was interpreted as MS being a low risk to most non-target soil microorganisms for the representative uses evaluated.

It was reported that MITC might have a low potential for ozone depletion but would be prone to long range transport. An MRL of 0.01* mg/kg was proposed for all representative crops.

The abovementioned review led to a change in approval of MS to be placed on the market[8]. While MS gained approval for continued placement on the market, the directive to withdraw existing authorisations for plant protection products containing metam as an active substance by 31 December 2014 and the conditions for its use were upheld.

[8] Official Journal of the European Union 26.4.2012

5 A case for Metham Sodium replacement

A shift away from sole reliance on chemical fumigants such as MS is desirable for several reasons. Even though MS offers an economically viable management option for growers, its efficacy due to enhanced biodegradation (Section 5.1.3), as well as the potential impacts to the environment and on human health make its continued use less desirable. This has been recognised in North America and Europe where the use of MS is more strictly controlled (via USDA and European Union Directives). Further, the drive towards limiting pesticide use (chemical reviews and deregistration of out-dated chemistry), tightening of international regulation (including MRLs) as well as a growing consumer demand for 'chemical free food and environments', support the case for MS replacement and the adoption of alternative management strategies.

The main drivers for MS replacement are summarised beneath.

5.1.1 Environmental impacts

MS has a high mobility in the soil and may move through the root zone faster than it is able to convert to the active MITC, the longevity and effectiveness of MS in the soil is therefore uncertain. This may also be contributing to an increased risk of leaching to groundwater and/or runoff to nearby waterways causing toxicity to fish and other aquatic organisms (APVMA 1997; Pruett et. al. 2001; NCAP 2006; Beyond Pesticides date n/a).

Research has found that MS results in long-term changes in the composition and activity of soil microorganism, with particular impact on nitrogen cycling microorganisms (Macalady et. al. 1998; Toyota et al. 1999). Macalady et. al. (1998) investigated the effects of MS fumigation on soil microcosms and found that MS has the potential to alter important microbially mediated functions such as nutrient cycling and pollutant degradation. These findings were also supported by Toyota et. al. (1999) who observed reductions in ammonium and nitrite oxidiser populations by up to four orders of magnitude following MS fumigation.

5.1.2 Fit with integrated production systems

The high Environmental Impact Quotient (EIQ)[9] of MS means it cannot be used as part of an integrated crop protection (ICP) approach.

The formula for determining the EIQ value of individual pesticides forms an average of impacts on the farm worker, consumer, and ecological impact components. It considers dermal toxicity, chronic toxicity, systemicity, fish toxicity, leaching potential, surface loss potential, bird toxicity, soil half-life, bee toxicity, beneficial arthropod toxicity and plant surface half-life.

5.1.3 Enhanced biodegradation

Repeated application of MS can lead to enhanced biodegradation of MITC substantially reducing the efficacy of MS for control of soilborne pests and diseases (Di Primo et. al.

[9] Kovach J. et al; 1992; A method to measure the environmental impact of pesticides. New York's food and Life Science Bulletin. 139. 1992 (http://www.nysipm.cornell.edu/publications/eiq/) http://www.nysipm.cornell.edu/publications/EIQ/default.asp

2003; Mattiessen et. al. 2004). Enhanced biodegradation occurs when there is an increase in soil microorganisms that are capable of rapidly degrading MITC.

Issues associated with enhanced biodegradation of MITC have been more prominent since the phase out of methyl bromide, which led to an increased use of MS and other chemical treatments (Martin 2003). Enhanced biodegradation can be prevented by using an integrated approach to pest and disease management (Section 6.4) and by not relying on a single chemical treatment (Hay et. al. 2013).

Box 6: Case study of enhanced biodegradation of MS (Warton et. al. 2001)

On a farm near Perth, WA, where MS has been extensively used for the past decade, a dramatic case of enhanced biodegradation has been identified. On this soil, the applied dose of MS produced less than half the maximum concentration of the toxin MITC reached in similar, previously untreated soil. Also, the MITC formed was present in the soil for less than 5% of the time of that in the untreated soil. On sterilisation of the affected soil in an autoclave, followed by treatment with MS, the MITC concentration/time relationship was similar to that of the previously untreated soil, confirming that the enhanced degradation was the result of a biological process. Dry heat treatment of the affected soil (100°C, 1 h) did not destroy the microorganisms responsible for enhanced biodegradation, as the soil recovered its degrading ability upon rehydration. This indicated that microorganisms with resistant stages were involved, at least in part, in the biodegradation of MITC.

Many growers appear to be aware of the existence of enhanced biodegradation but do not know whether their paddocks are affected. Product reviews in other countries have shown that earth worms are especially affected by MS and that they do not return for at least 12 months after application. The fact that growers report finding worms not long after MS use may indicate that MS is breaking down quickly in their paddocks. Some degraded soils may be free of worms, whether treated or not, which means they could not be used as a universal indicator of enhanced biodegradation.

5.1.4 Human health impacts

In the United States, MS is listed as a carcinogen and development toxicant. Respiratory, eye and throat irritation, diarrhoea and rash are some symptoms of exposure to MS. Symptoms of MS poisoning in exposed people include burns, eye irritation, difficulty breathing, nausea, diarrhoea, anxiety, and blurry vision. Poisonings have occurred as far as a mile from the application site[10]. In laboratory animals, MS caused a wide variety of health effects. These include a reduction in the activity of immune system cells, a reduction in the levels of the hormone that triggers ovulation, a reduction in leg strength, a reduction in activity, anaemia, damage to the lungs, and damage to the liver. Both the U.S. Environmental Protection Agency (EPA) and the California EPA classify MS as a carcinogen (a compound that causes cancer). These classifications are based on laboratory studies in which MS exposure caused malignant tumours. California EPA also classifies MS as a

[10] Cox C. 2006; Metam Sodium. Journal of Pesticide Reform/ SPRING 2006 • VOL. 26, NO.1

reproductive toxicant because it has caused pregnancy loss in laboratory studies. Reports about chronic health issues due to repeated exposure to MS were not found.

MS is listed as an air contaminant (APVMA 1997; Pruett et. al. 2001; NCAP 2006; Beyond Pesticides date n/a).

5.1.5 Diminishing chemical options

The increasing cost of agricultural chemicals, tightening regulation around their use, review and deregistration (MS has already been phased out in many EU countries – refer to Section 4) means the chemical options available to growers are becoming increasingly limited. Therefore growers should not rely solely on a specific chemical treatment for pest and disease control, due to the increasing uncertainty of its continued availability (Hay et. al. 2013). Alternatives should be trialed on farm before an active ingredient is due to be lost.

Note: At the time of writing this report the APVMA has no plans to review MS and related compounds (Alan Norden, pers. comm.).

5.1.6 Consumer demand

Ironically, in the past consumer demand for high quality, uniform products may have driven the use of MS, particularly in intensified production systems. However now an increasing consumer desire for “no residue, safe food” may be driving a shift away from chemical use. Still, the demand for the perfect vegetable will remain, which puts a rising pressure on growers’ production systems and may increase the amount of product wasted because it does not meet strict ‘appearance standards’.

There is considerable interest from consumers regarding the environmental impact of products they consume; they want to know that they are sustainable, and business partners want to know that the companies they deal with are ethical (AUSVEG 2013a).

5.1.7 Trade and export restrictions

As international regulations tighten around the use and application of MS in other countries (refer to Section 4), this may restrict future trade and export opportunities for Australian growers using MS. MS alternatives may be important in order to comply with international regulations and remain competitive on the international market.

Current maximum residue limits (MRLs) for MS in levy vegetables are included in Appendix 3. Importing countries set their own MRLs, the levels provided in Appendix 3 do not necessarily apply to export markets. In the main, MRLs for vegetables in Australia are significantly below the level recommended for all crops in the EU (0.01* mg/kg, Section 4.2). Existing and new export markets for carrots could pick up the on the MS reviews conducted in Europe and the US and thus set low MRLs for MS; this may then affect producers’ ability to export.

6 Alternatives to Metham Sodium

Fumigants such as MS have long been essential to many intensive vegetable production systems that are driven by the need for high productivity. Market pressures require low cost of production (tight margins) and high marketable yields (of 'perfect' vegetables). This reliance is making it difficult to find, and transition to, suitable alternatives.

The prolonged customary use of MS means that in many cases growers feel "locked-in" to ongoing applications of the soil fumigant and do not have much confidence in alternatives to move away from MS. As such, demonstrable efficacy, cost-effectiveness and ease of use will be required of any potential alternative/s (see Section 6.1). Many growers have tried alternatives with varying enthusiasm and results.

While chemical and non-chemical alternatives do exist, very few of them offer a direct and easy "drop-in" replacement for MS; and they are most effective when accompanied by broader alterations in the production system (Martin 2003). This therefore demands a significant shift in grower aspirations, knowledge & skills, mindsets and practices.

The chemical and non-chemical alternatives to MS are discussed in detail in Sections 6.2 to 6.9.

6.1 Requirements of alternatives

Grower confidence in MS remains high in the absence of alternatives that provide a similar level of costs, ease of use and perceived effectiveness (even though the efficacy of MS appears increasingly uncertain, Box 7).

Box 7: Australian Potato Research Program 1, Technical Summary on MS trials[11]

> Pre-plant fumigation with metham sodium did not reduce the incidence of Black scurf, Powdery scab or Common scab, or improve the yield or quality of potatoes. Two field trials were conducted to evaluate the effect of green manure incorporation on soilborne disease and soil microbiology. Incorporation of brown mustard (Brassica juncea) resulted in a 56% reduction in Black scurf, and reduced eel worm, Powdery scab and Common scab, as well as increasing soil biological activity. In the second trial, green manure crops BQ mulch, ryecorn, lupins, ryecorn + lupins had no effect on the incidence of these diseases. Since disease overall was low, it is thought that the effect of drought masked any effect of the green manure crop. The incorporation of these plant residues, however, did increase soil active carbon and biological activity.

There is a suite of reasons supporting a shift away from MS reliance (presented in Section 5), however in order for alternative management options to be attractive to growers they need to meet requirements, such as affordability and practicability. Additionally, a fundamental requirement of any alternative is to provide better environmental and human health outcomes than MS.

[11] Horticulture Australia Report - PT04016 (p20)

The following points highlight some of the requirements that potential alternatives to MS will need to incorporate:

- Economic viability (short and / or medium to long term)
- Ease of use
- Reliability and proven effectiveness in managing target organisms
- Fit with rotations, soils and current infrastructure
- Have minimal impact on the environment and other crops
- Have minimal human health impacts for users and the broader community
- Have reduced potential of resistances developing and/or the occurrence of enhanced biodegradation, providing long-term sustainability.

6.2 Chemical alternatives

There are some chemical alternatives to MS, such as non-volatile nematicides and other fumigant nematicides. Some new generation nematicides are under development and new fungicides have been registered overseas; these may become registered in Australia.

Relying on chemical alternatives to MS alone should however remain a temporary solution and in the long term less chemical control should be needed (Davison & McKay 2013). Developments in Europe and the US provide examples of improved stewardship of MS and alternative management options. Hay et. al. (2013) points out that growers cannot assume that effective chemical products will always be available. In many cases, chemical alternatives have questionable long-term viability due to rising costs, limited efficacy (biodegradation, resistance), and use restrictions, which could include expanded buffer zones to protect health (CDPR 2013). For example, 1,3-Dichloropropene (1,3-D) has been banned in the EU, this may make its future use in Australia uncertain.

Issues associated with enhanced biodegradation of repeated chemical use remain a concern. Chemical use, such as repeated soil fumigation, depletes the soil of beneficial soil organisms many of which act as natural biological control agents against pathogens and pests (disease suppression)[12]. A depletion of beneficial soil organisms and organic matter (due to high use intensity of soils/tillage in intensive cropping systems) effectively commits the grower to repeated chemical applications to control pests and diseases.

Appendix 4 offers a summary of the potential soil applied chemical alternatives to MS.

The following sections provide detail on a wider range of alternatives.

[12] Zhi-Ping, C. et al. 2004. Impact of soil fumiga- tion practices on soil nematodes and microbial biomass. Pedosphere 14:387-393.
Schreiner, R.P., K.L. Ivors, and J.N. Pinkerton. 2001. Soil solarization reduces arbuscular mycor- rhizal fungi as a consequence of weed suppres-sion. Mycorrhiza 11:273-277.
de Jong, F.M.W, E. van der Voet, and K.J Canters. 1995. Possible side effects of airborne pesticides on fungi and vascular plants in The Netherlands. Ecotoxicol. Environ. Safe. 30:77-84.
Toyota, K. et al. 1999. Impact of fumigation with metam sodium upon soil microbial community structure in two Japanese soils. Soil Sci. Plant Nutr. 45(1):207-223.

6.2.1 Broad spectrum fumigants

Calcium cyanamide

Calcium cyanamide or $CaCN_2$ is a calcium compound, which was initially developed for use as fertiliser. General benefits are:

- Slow release nitrogen fertiliser
- Ready source of calcium – 50% CaO
- Stabilises soil pH
- Improves soil structure with repeated use
- Cyanimide is a feedstock for soil microflora.

In contact with water, calcium cyanamide is decomposed in several steps into lime and plant available nitrogen. In the first step calcium cyanamide is transformed into hydrated lime and cyanamide. A small portion of the cyanamide then forms dicyandiamide (DCD) in the soil. DCD is well known as a nitrification inhibitor. That means that the transformation from urea to ammonia, ammonium nitrogen and then to nitrate nitrogen in the soil is slowed down significantly as the DCD inhibits the activity of the soil bacteria Nitrosomonas.

In the first days after spreading, calcium cyanamide can affect germinating seeds, small upcoming weeds and soil borne pathogens (e.g. *Rhizoctonia solani*, *Fusarium oxysporum* and *Verticillium dahliae*[13]). The product has been used for a long time to control clubroot in brassica crops and *Sclerotinia* in lettuce.

Toxic cyanide gas is not released during this decomposition. Calcium cyanamide is environmentally benign. Cyanamide, which causes the specific effects of calcium cyanamide, remains dissolved in soil water. Its fumigating effects last for about 8-14 days in the soil, depending on decomposition conditions, until the cyanamide is totally converted to plant available nitrogen. The duration of the decomposition phase depends on soil humidity, soil temperature, microbial activity, humus content of the soil and application rate of calcium cyanamide.

Ethanedinitrile (EDN)

Ethanedinitrile (EDN) has been developed with the CSIRO and BOC as an alternative to the soil fumigant methyl bromide. Current use targets for registration are the fumigation of timber and soil disinfestation in the nursery production of strawberries. Compared to Methyl Bromide, EDN is ozone friendly.

In microplot studies it was found that EDN killed buried inoculum of several soilborne pathogens (*Pythium ultimum*, *Phytophthora cactorum*, *Fusarium oxysporum* and *Rhizoctonia* spp.) and reduced natural populations of plant-parasitic nematodes (*Tylenchus* and *Helicotylenchus* spp.) to levels equivalent to methyl bromide (Mattner et. al. 2006). In field trials, EDN reduced the emergence of weeds by 98% and increase strawberry runner yields by 135%, which is equivalent to methyl bromide (Mattner et. al. 2006).

[13] Wang, L.et al, 2007; Inhibitory efficacy of calcium cyanamide on the pathogens of replant diseases in strawberry. Frontiers of Agriculture in China, Volume 1, Issue 2.

Testing of EDN showed that the gas required lower doses (and exposure times) to have the same effects as methyl bromide on common soil insects, nematodes and fungi. This is a huge advantage for public and worker safety since the chance of toxic exposure is decreased two-fold (Nordiko Quarantine Systems 2013).

The APVMA supported the approval of the active ethanedinitrile and registration of Sterigas® 1000 Fumigant containing 1000 g/L ethanedinitrile for use as a fumigant for the control of pathogens, weeds and insects in timber. The public release summary was published in June 2013[14].

BOC is working on the registration for the active as a soil fumigant for the production of strawberry runners. Limited trials have been conducted in vegetables (capsicums). Given the product is produced in Australia and has a good chance to be registered, trials should be conducted in other vegetable crops.

In Germany, EDN is distributed as EDN FUMIGAS® for soil by The Linde group (cropscience.linde-gas.com) for the fumigation of timber and as a soil fumigant.

Typical examples for Fumigas® use are:

Dose rate: 150–500kg/ha depending on the pest of concern and level of infestation

Application techniques: Shank Injection (injected into the soil through tractor tynes), chemigation (mixed with water and injected into the soil through pre-laid drip tape)

Commodities: fruit: strawberry (including nursery stock), capsicums, cucurbits, watermelon, tomato; other: ginger, cut flowers

Pest/disease: Soil borne Pathogens: *Pythium ultimum, Phytophthora cactorum, Fusarium oxysporum, Rhizoctonia fragariae, Sclerotinium rolfsi, Pythium sulcatum, Rhizoctonia solani, Fusarium acuminatum, Phytophthora cryptogea, Bipolaris soroikiniana* **Nematodes**: *Meloidogyne* spp., *Steinernema* spp.

Weeds: *Poa annua, Spregula arvensis, Agrostis tenuis, Raphanus raphanistrum Conyza Canadensis, Lolium sp. Solanum nigrum, Amaranthus retroflexus, Portulaca oleracea, Orobanche aegyptiaca, Cyperus rotundus*

Note: root and brassica vegetables are not included in the above example for registered EDN use in Germany.

Methyl iodide (iodomethane)

Methyl iodide was trialed in several countries for use as a fungicide, herbicide, insecticide, nematicide, and as a soil fumigant to replace methyl bromide (banned under the Montreal Protocol). Japan based Arysta LifeScience sells methyl iodide under the brand name MIDAS. Methyl iodide is registered as a pesticide in the U.S., Mexico, Morocco, Japan, Turkey, and New Zealand and may be registered other countries including Australia.

[14] http://www.apvma.gov.au/registration/assessment/docs/prs_ethane_dinitrile.pdf

The use of methyl iodide as a fumigant has drawn concern. In 2007, 54 chemists and physicians contacted the U.S. EPA in a letter, saying "We are skeptical of U.S. EPA's conclusion that the high levels of exposure to methyl iodide that are likely to result from broadcast applications are 'acceptable' risks.[15]

The California Department of Pesticide Regulation (DPR) concluded that methyl iodide is "highly toxic," that "any anticipated scenario for the agricultural or structural fumigation use of this agent would result in exposures to a large number of the public and thus would have a significant adverse impact on the public health", and that adequate control of the chemical in these circumstances would be "difficult, if not impossible[16]." A lawsuit was filed on January 5, 2011, challenging California's approval of methyl iodide. Subsequently, Arysta LifeScience withdrew the fumigant from the US market.

Even though methyl iodide was trialed in Australia in a range of crops against common soil borne pests and weeds including vegetables and its efficacy at an adequate application rate may be established, it does not provide a viable alternative to MS based on its toxicity.

Propylene Oxide

The United States Food and Drug Administration approved the use of propylene oxide to pasteurize raw almonds beginning on September 1, 2007 in response to two incidents of contamination by *Salmonella* in commercial orchards, one incident occurring in Canada, and one incident in the United States. Pistachio nuts can also be subjected to propylene oxide to control *Salmonella*.

The product has been considered as a replacement for Methyl Bromide in vegetables. It is not registered in Australia.

Studies in animals have demonstrated that propylene oxide is a direct-acting carcinogen[17] it therefore does not provide a viable alternative to MS.

6.2.2 Seed treatments

Seed treatment provides an effective way of protecting emerging crops to achieve fast, even establishment and resilient plants.

A prerequisite for good results from seed treatment is to only use high quality, high vigour, and healthy seed. Many diseases can be carried on or in seed. Germ testing is recommended. New seed dressing technologies and products may be used effectively to protect crops in the early phases of establishment when they are especially vulnerable. Seed treatment is an important part of integrated crop protection (ICP, Section 6.9).

Treatment of vegetable seeds is routinely used to kill pathogens carried within or on the seed and to protect the seed or seedling from 'damping-off' diseases. This is especially important when seed is planted in cold or warm wet soil or is slow to germinate. Seed treatment can be useful in reducing the amount of pesticide required to manage diseases

[15] Keim, Brandon, 2007; Scientists Stop EPA From Pushing Toxic Pesticide.
[16] Special Scientific Review Committee of the California Department of Pesticide Regulation. 2010; Report of the Scientific Review Committee on Methyl Iodide to the Department of Pesticide Regulation.
[17] WBK & Associates Inc., 2002: Assessment Report on Propylene Oxide for Developing an Ambient Air Quality Guideline. Prepared for Alberta Environment. Edmonton, Alberta, Canada.

later on. This reduction in pesticide use is both economically and environmentally beneficial. Treatments may disinfect (kill pathogens borne within the seed), disinfest (kill externally born pathogens), or protect the seed.

Globally, crop protection producers have a range of seed treatments to control soilborne pests disease in vegetables including *Pythium*, *Phytophthora*, *Fusarium*, *Rhizoctonia*, nematodes and early season chewing insects / soilborne grubs (wireworm etc). The expense of registering these products in the Australian market unfortunately makes it hard to develop these here.

However, a range of products and application technologies are available and appropriate seed dressing products should be selected depending on disease risks. New seed treatment products often combine fungicides with an insecticide to provide protection against a broad spectrum of early-season diseases and insects. Nutrients can be added to seed dressings to provide easy access to nutrients e.g. phosphorus or trace elements during emergence.

Cleaning and grading gives better emergence in the field due to a more uniform seed size, improved seed treatment application, optimised drill performance and more even spacing in the field.

Steeping of seed where appropriate can penetrate deep into the seed coat and remove germination inhibitors from the seed to facilitate even germination. Additional use of active ingredients can remove seed borne pathogens.

Priming can be an option to improve speed of germination and help to improve crop uniformity. Priming encourages more uniform emergence and better crop establishment. It helps with decision making for and efficacy of further pest and disease management because all plants are at a uniform growth stage. Uniform, fast establishing crops compete better against weeds, aiding with reduction in herbicide usage. Improved uniformity can carry through to the final harvested product, and increase marketable yield.

Filmcoating involves the application of plant protection to seed in polymers using special equipment giving a glossy, smooth finish to seed, reducing the risk of irregular drilling patterns by improving seed flowability. A range of colours can be applied to add contrast and increased visibility against soil. Filmcoating can use very small amounts of active ingredient and has very low dust levels in the treated seeds, making operator handling safe and reducing the risk of dust exposure in the environment.

Pelleting allows for improvements to be made to the natural seed shape, with the option to add plant protection products onto the pellet surface. Pelleting adds weight to light seed, allowing for better flow through seed drills. A uniform shape also helps with drilling, leading to a more uniformly established crop. Pelleting results in greater surface area for application of plant protection products.

Even though specific state of the art seed treatments may appear expensive, the results in better crop performance should easily outweigh the costs. Cheap seed can become very expensive if it contains pathogens and/or is not protected using the best possible technology.

Products

HAL project VG04021, “Evaluation of new seed dressings for improved disease and insect control in vegetable crops” investigated fungicide dressing formulations containing the active ingredients azoxystrobin, fludioxonil, metalaxyl-M and difenconazole and two insecticide seed dressings with abamectin or thiamethoxam. The products were examined at different rates to identify the appropriate concentrations for use on different vegetable groups against the main damping off pathogens and insects affecting early establishment. The seed dressings were compared with untreated control seeds and thiram treated seeds. All fungicides proved to be effective alternatives to thiram with the same or better control of target diseases.

Apart from the abovementioned products tested for the vegetable industry, a range of other active ingredients are available and information on the best product and treatment technology options for individual situations should be sought from suppliers and local experts.

6.2.3 Nematicides

Non-volatile nematicides

Non-volatile nematicides temporarily inactivate nematodes by preventing egg hatch, reducing mobility, inhibiting feeding and retarding development. They are incorporated into the soil or transported by water to the upper 10 cm of the soil prior to planting, thus creating a zone of protection for germinating seeds.

Non-volatile nematicides are only effective in the soil for a period of 2–8 weeks. They are also relatively mobile, particularly in sandy soils with little organic matter, meaning they can leach into shallow water tables. They are rated as highly toxic S7 poisons, which act on the nervous system of nematodes and other animals.

The future use of non-volatile nematicides in Australia is uncertain. For example, Fenamiphos is banned in the USA and is facing withdrawal in Australia (Hay et. al. 2013).

Enhance biodegradation is also known to occur for Fenamiphos (sold under the product name Nemacur in Australia).

1,3-D and Chloropicrin

In Australia, Telone (1,3-D) and Telone C35 (1,3-D and Chloropicrin) have found to be effective in controlling nematodes in field trials in WA carrot crops providing an alternative to MS and Fenimaphos for nematode control (Davison & McKay 2013). Table 6-1 demonstrates the effect of Telone and Telone C35 treatment on carrot seedlings in a WA field trial (Hay et. al. 2013).

Telone is of greater interest as a nematicide for carrots as it is less than half the cost per hectare of Telone C35, however the latter provides broader fumigation to help control a range of soilborne diseases (Davison & McKay 2013). Both products require injection into the soil. The application cost of both Telone, and in particular Telone C35, remains greater than that of MS, especially at higher rates (Telone C35 about $3,500-4,400/ha, and Telone at $1000-1500/ha). The costs need to be weighed against the effectiveness of the products.

Davison & McKay (2013) emphasise that both Telone and Telone C35 need to be managed to avoid the development of enhanced biodegradation from repeated use, and as such more integrated approaches to nematode control are desirable in the medium to long term.

Table 6-1 Effect of fumigant treatment carrot seedlings and at harvest in a Western Australian field trial

Treatment	% Seedlings with egg masses (%) at 45 days after planting	Export quality carrots at harvest (weight %, @ 136 days)	Forked carrots at harvest weight %, @ 136 days
Telone at 130kg/ha	0	45.3	0.3
Telone C35 at 270kg/ha	3.2	46.1	0
Telone C35 at 185kg/ha	1.9	47.6	0.5
Untreated control	34.1	10.7	48.6

Abamectin

Registration of Abamectin (Tervigo) as a nematicide for use with drip irrigation on cucumbers and capsicums (at planting and repeated after 4-6 weeks), if successful, will provide an alternative for the control of nematodes in these crops. Registration for carrots is not planned based on the limited mobility of the product in soils, which would prevent efficacy, especially when used post planting.

New nematicides

Hay et. al. (2013) identified two new generation nematicides that are under development and may become registered for carrots in Australia:

- Fluensulfone: applied as a soil drench is lethal to nematodes on contact. It has a lower toxicity than Fenamiphos with a re-entry period of 12 hours.

- Spirotetramat: a ketoenol insecticide which reduces egg production and viability when ingested by immature stages of suckling insects e.g. aphids, psyllids, scale, leafminer, thrips, mealybugs and whiteflies. Also exhibits activity against plant-parasitic nematodes.

6.2.4 Soil applied fungicides

The most common fungi affecting carrot crops are *Fusarium, Pythium* and *Rhizoctonia* species. The number of fungicides available to treat these fungi in soils is limited, hence the reliance on MS which provides effective control for all three. Most fungicides against soil borne diseases are applied as seed dressing or to banded in soils prior to planting.

Metalaxyl

Fungicides containing Metalaxyl or Metalaxyl-M can provide some control of *Pythium* and *Phytophthora* in carrots, cucurbits, capsicums and brassica crops (cabbage, cauliflower, boccoli, brussels Sprouts). The Product Ridomil Gold 25 G can for instance be used at 40 kg/ha or 120 g/100m row preplanting across a range of vegetable crops including carrots, brassicas, capsicums, cucurbits and tomatoes. The formulation as a wettable granule makes it somewhat awkward to use (Syngenta, pers. comms 2014). Therefore trials are underway to demonstrate bioequivalence (efficacy and safety) of Ridomil Gold 480 SL which could be used as a soil applied spray similar to use in potatoes. Chemigation options are also under investigation. Registration of the new formulation by APVMA is expected to be about 15-18 months away.

Enhanced degradation of metalaxyl has been reported in sites that have a history of consecutive years of metalaxyl soil applications[18]. This observation was confirmed by Syngenta (pers. comms 2014). In soils with an enhanced degradation problem, metalaxyl breaks down so rapidly that it does not provide appropriate disease control. For example, in a sandy soil that had no prior history of metalaxyl application, its half-life was 82 days. This was reduced to as little as 4 to 10 days in paddocks with enhanced degradation. In laboratory studies, a single exposure of different soils with no history of metalaxyl treatment was sufficient to increase their subsequent capacity to degrade the fungicide. This may be due to the wide range of microorganisms (fungi, bacteria and actinomycetes) capable of degrading it. High microbial activity in soil is usually associated with high organic matter levels. Therefore, metalaxyl tends to degrade faster in soils that are high in organic matter. Rapid degradation was found in intensively cropped soils, where the fungicide had been applied to soil in carrot and potato crops in consecutive years. It is not known whether affected soils can recover from enhanced metalaxyl degradation.

Metalaxyl resistance has been reported for a range of crops when the active was overused against a specific pathogen (e.g. downy mildew in onions).

Azoxystrobin

Azoxystrobin is the active ingredient in Amistar and registered for use in carrots against Alternaria in carrots and brassica vegetables. Plans are to look at application options as a soil drench.

[18] Pung, H. 2002; Enhanced metalaxyl breakdown and its implication in Australian horticulture. Horticulture Australia Limited report VX00012

6.2.5 Herbicides

MS is active against weeds. If fungicides and/or nematicides replace it, a need for weed control remains. A range of pre and post-emergent herbicides is available in Australia. Consultation with producers of crop protection products revealed that new developments in herbicides for vegetable crops are unlikely. In production systems, MS would have to be replaced by an effective pre-emergent and post-emergent herbicide program.

6.3 Biopesticides and biological control

6.3.1 Biopesticides

Developments in biopesticides

The development of biopesticides is rapidly increasing with most major crop protection producers now developing and marketing products that contain non-synthetic ingredients derived from animals, plants, microbes, or some minerals. The products are frequently supplemented with trace elements or other minerals. Humic acid may be added if products are to be applied to soils. As for synthetic (chemical) pesticides, the target crops for these products are often grains, maize and cotton due to the market size. Often registration or use patterns (if registration is not required) for horticultural crops are developed once a product is established in the major crops. Generally biopesticides products have short or no withholding periods and are suitable for inclusion in ICP programs.

This section on biopesticides expands on their general use. This has been done because these types of products and control methods are/would be important components of an overall ICP approach (ICP, section 6.9) aimed at improving the overall soil and crop health status by suppressing diseases and increasing crop resilience.

It is recommended to keep a watching brief on new developments by talking to crop protection company representatives and following relevant publications e.g. through http://www.agra-net.com/.

What are biopesticides?

Biopesticides are a diverse group of non-synthetic pest control products that are relatively non-toxic to mammals (including people) with few environmental side effects. Many can be used in organic production. Some of these products require thorough coverage, application before or at the first signs of disease, and often repeated applications to be effective. They require a good understanding of pests and diseases that need managing and are best used in an integrated approach rather than a ‘drop-in’ replacement of a specific synthetic pesticide.

In the US, as of early 2013 there were approximately 400 registered biopesticide active ingredients and over 1250 actively registered biopesticide products. Categories of biopesticides include:

I. Microbial pesticides, in which a microorganism (e.g. a bacterium, fungus, virus or protozoa) is the active ingredient

- Microbial pesticides are formulated microorganisms or their by-products. They tend to be selective, so specific pests may be controlled with little or no effect on non-target organisms. Microbial insecticides may be derived from bacteria (e.g. *Bacillus thuringiensis*, *spinetoram* and *spinosad*, *Chromobacterium subtsugae*), virus (e.g. nuclear polyhedrosis virus of corn earworm) or fungi (e.g. *Beauvaria bassiana*). Microbial disease control products are living organisms, including beneficial fungi and bacteria.

II. Plant-Incorporated-Protectants (PIPs), in which pesticidal substances are produced by crop plants as a result of genetic material that has been added to the plant (e.g. Bt pesticidal protein)

III. Biochemical pesticides, which are naturally occurring substances that control pests by non-toxic mechanisms, such as sex pheromones that interfere with mating and various scented plant extracts that attract insect pests to traps or insect growth regulators (IGR), which interrupt or inhibit the life cycle of a pest

IV. Organic pesticides

- Botanicals that are plant-derived materials such as pyrethrin, azadiractin, and extract of *Chenopodium ambrosioides* or garlic. Plant-derived oils such as neem, canola, jojoba linseed, sesame, soybean, garlic and cottonseed oil and essential oils (e.g. rosemary, mint, thyme, geranium, lemongrass, cinnamon and rosemary) are also included in this group. Botanicals are generally short-lived in the environment, as they are broken down rapidly in the presence of light and air. They are mainly used in organic production.
- Altered natural materials that are heated, chemically reacted, or mixed with surfactants. Examples for minerals are kaolin clay, copper compounds and iron phosphate; others examples are sulphur, potassium bicarbonate, and phosphites used to control fungal and bacterial diseases They may work to control the target organism or by strengthening plant defences. Some of these products could be considered synthetics. Only few organic pesticides are useful for controlling soilborne pests and diseases; phosphites are the main active ingredient.

See Appendix 5 for information on biopesticides to control soilborne pests and diseases. The tables provide examples demonstrating the potential for biopesticides; they are not a listing of products that are all currently available or would necessarily all be effective for use in vegetables under Australian conditions. The tables include products that have to be registered as pesticides as well as some that might be exempt. Active ingredients that are available in Australia are identified in the tables.

6.3.2 Biopesticides with potential to replace Metham Sodium

The active ingredients/fungicides listed below are currently not available/registered in Australia for vegetable crops. They are listed because they appear to be suitable replacements for MS on their own or if combined with other management methods. Efforts should be made to investigate the potential to obtain access to these products for trials in Australia.

Serenade® SOIL biofungicide

Serenade® Soil is registered in US (apart from California for most applications) and Canada as a biofungicide with the following active ingredient: 1.34% of QST 713 strain of *Bacillus subtilis*. The product can be applied to the soil via sprayers, tyne injection or irrigation systems. The label and MSDS provides detailed instructions (http://www.cdms.net/LDat/ld9HQ032.pdf).

According to the producer AgraQuest, a subsidiary of Bayer Cropscience, applied at planting or transplanting, Serenade® SOIL first attacks soil-dwelling pathogens, and then quickly builds a disease protection zone around the seed. As the seedling grows, the beneficial bacteria in Serenade® SOIL continue to grow, attaching themselves to the roots of the plant, expanding the disease protection zone.

Serenade® Soil is registered in the US against the following fungal diseases in vegetables:

- Root and Tuber vegetables: *Rhizoctonia* spp., *Pythium* spp., *Fusarium* spp., *Verticillium* spp., *Phytophthora* spp., *Erwinia* spp.
- Brassica vegetables: *Rhizoctonia* spp., *Verticillium* spp., *Plasmodiophora brassicae* (Clubroot)
- Leafy vegetables: *Rhizoctonia* spp., *Verticillium* spp., *Sclerotinia* spp.
- Curcurbits: *Rhizoctonia* spp., *Pythium* spp., *Fusarium* spp., *Verticillium* spp., *Phytophthora* spp.
- Bulb vegetables: *Phoma* spp. (Suppression)
- Corn: *Rhizoctonia* spp., *Pythium* spp. *Fusarium* spp.
- Legume vegetables (Succulent or Dried): *Rhizoctonia* spp., *Pythium* spp., *Fusarium* spp., Verticillium spp., *Phytophthora* spp., Peanuts also: *Cylindrocladium* Black Rot *Sclerotium rolfsii*
- Fruiting vegetables: *Rhizoctonia* spp., *Pythium* spp., *Fusarium* spp., *Verticillium* spp., *Phytophthora* spp.

Target diseases most in fruit crops are: *Pythium* spp., *Phytophthora* spp., Strawberries: *Verticillium dahliae*.

Application rates for all vegetables are 2-6 L/ha; however, the producer AgraQuest has put forward a recommendation for a reduced rate to root and tuber vegetables of 1-2L/ha against *Rhizoctonia* spp., *Pythium* spp., *Fusarium* spp., *Verticillium* spp., *Phytophthora* spp., *Plasmodiophora brassicae* (Clubroot) *Streptomyces scabies (*Suppression of Common Scab in potatoes).

Serenade® Soil can be used in combination with other registered fungicides. Bayer Australia could not comment on plans regarding the product's potential registration in Australia.

Regalia® RX biofungicide

Regalia® is a Marrone Bio Innovations, Inc. biofungicide based on a plant extract to boost the plants' defence mechanisms through Induced Systemic Resistance (ISR) and protect against certain fungal and bacterial diseases, and to improve plant health. The active ingredient is a 5% extract of *Reynoutria sachalinensis*. It is registered in the US for the control of a range of foliar fungal diseases in broad acre crops and cotton. It is also registered for peanuts as a soil drench against *Aspergillus niger*, *Fusarium* spp., *Phytophthora* spp., *Pythium* spp., *Rhizoctonia* spp., *Verticillium* spp. and *Sclerotium* rolfsii.

The product can be mixed or used in a program with other fungicides. It is especially suited to Integrated Crop Protection. ICP. It has no withholding period apart from excluding workers from treated crops for a minimum of 4 hours. No MRLs are required.

MBI-601 EP biofumigation product

Marrone Bio Innovations, Inc., has submitted MBI-601 EP, a biofumigant product, to the United States Environmental Protection Agency (EPA) for registration in April 2014[19]. The product controls and suppresses plant parasitic nematodes, insect pests and soilborne plant diseases in agricultural and horticultural soils. The active ingredient, *Muscodor albus* strain SA 13, produces volatile compounds that inhibit the growth of or kill plant pests and diseases. It targets the most destructive species of nematodes—root knot, sting, ring, spiral, cyst, lance, and lesion and also the highly damaging plant diseases *Fusarium* root rot, damping off, southern blight and *Verticillium* wilt. With the use of this biofumigant, field trials show increased yields in treated strawberries, lettuce and other crops.

MBI-601 is a naturally occurring, biologically-based fumigant designed to provide an alternative to the traditional synthetic materials. Following is information from the US Patent application dated September 2013 and publicised 27 March 2014[20]: "Disclosed herein is an isolated *Muscodor albus* strain producing volatile organic compounds such as aristolene, 3-oc tanone and/or acetic acid ester, as well as cultures of said strain and compositions, metabolites and volatiles derived from said strain or culture as well as methods of obtaining said compositions, metabolites and volatiles and their methods of use for controlling pests. Also disclosed are artificial compositions having the same components and uses as the volatiles derived from the strain. A method for capturing and sampling the volatiles is also disclosed."

6.3.3 Biological control (biocontrol)

What is biological control?

'Biological control' describes the use of living organisms that suppress pests or diseases; they compete with plant pathogenic fungi, produce toxic metabolites, or actively parasitize pathogens. They may be naturally occurring in soils or soil amendments (e.g. composts) or lab-reared and produced and released or applied by the grower. These are not regulated by the APVMA and are allowed in organic production.

[19] http://www.marronebioinnovations.com/2014/04/marrone-bio-innovations-submits-biofumigant-for-epa-registration/#sthash.fvvISa8B.dpuf
[20] http://www.google.com/patents/US20140086879 for patent details

Biological control of insect pests is taking place in vegetable crops all the time, because native and naturalised populations of natural enemies live on farms and move into crops to feed on or lay their eggs into pest insects. Predators consume several insects over the course of their development. Parasites (also called parasitoids) tend to lay eggs in their host insect, which hatch into larvae that feed internally, develop and kill the host. Pathogens invade the body of the host insect. The impact of beneficial insects is often underestimated because it is easy to overlook and difficult to measure. This may become obvious if broad-spectrum insecticides kill them and pest outbreaks occur as a result.

Similarly, biological control of soilborne diseases can occur naturally; this requires the soil to have a high level of biodiversity (macroscopic and microbial soil life).

Biological Disease Control Products contain living organisms, which require specialised storage and application procedures. Their effectiveness in research trials has been inconsistent because of variations in environmental conditions and disease pressure. Microbial fungicides and insect pest controls perform best in a greenhouse environment where they can establish and flourish. Control of plant pathogenic organisms on the leaf surface or in the soil are especially problematic, as the competing organisms must establish themselves and can fail due to desiccation, competition, water logging or exposure to sunlight. The 'materials' have a limited shelf life, must be protected from temperature extremes, and correctly used for effectiveness.

Disease suppression

Microbes that contribute most to biological disease suppression are most likely those epiphytes and endophytes that could be classified competitive saprophytes, facultative plant symbionts and facultative hyperparasites. These can generally survive on dead plant material, but they are able to colonize and express biocontrol activities while growing on plant tissues.

Due to the ease with which they can be cultured, most biocontrol research has focused on a limited number of bacterial (*Bacillus, Burkholderia, Lysobacter, Pantoea, Pseudomonas, and Streptomyces*) and fungal (*Ampelomyces, Coniothyrium, Dactylella, Gliocladium, Paecilomyces, and Trichoderma*) genera. Still, other microbes that are more difficult to grow in vitro culture have been intensively studied. These include mycorrhizal fungi, e.g. *Pisolithus* and *Glomus* spp. that can limit subsequent infections, and some hyperparasites of plant pathogens, e.g. *Pasteuria penetrans* which attack root-knot nematodes.

Multiple infections usually occur in crops; therefore weakly virulent pathogens can contribute to the suppression of more virulent pathogens, via the induction of host defences.

Soil microbial diversity supported by adequate levels of organic matter should support natural disease suppression.

Mycorrhiza

While various epiphytes and endophytes may contribute to biological control, the ubiquity of mycorrhizae deserves special consideration. Mycorrhizae are the result of symbioses between fungi and plant roots; they occur on over 95% of plant species. Because they are formed early in the development of the plants, they represent nearly universal root colonists that assist plants with the uptake of nutrients (especially phosphorus and micronutrients) and water. During colonization, VAM fungi (vesicular-arbuscular mycorrhizal fungi) can prevent root infections by reducing the access sites and stimulating host defence. VAM fungi have been found to reduce the incidence of root-knot nematode (Linderman 1994). Various mechanisms also allow VAM fungi to increase a plant's stress tolerance. This includes the intricate network of fungal hyphae around the roots, which block pathogen infections. VAM fungi protect the host plant against root-infecting pathogenic bacteria. The mechanisms involved in these interactions include physical protection, chemical interactions and indirect effects. The other mechanisms employed by VAM fungi to indirectly suppress plant pathogens include enhanced nutrition to plants; morphological changes in the root by increased lignification; changes in the chemical composition of the plant tissues like antifungal chitinase, isoflavonoids, and others. (Morris and Ward 1992); alleviation of abiotic stress and changes in the microbial composition in the mycorrhizosphere (Linderman 1994).

In contrast to VAM fungi, ectomycorrhizae proliferate outside the root surface of many woody plants and form a sheath around the root by the combination of mass of root and hyphae called a mantle. Vegetables do not have ectomycorrhizae. Vegetables and potential rotational crops that form an association with VAM are listed below.

Respond to VAM		**No response**
Alfalfa	Melons, all	Brassica family e.g.:
Asparagus	Millet	▪ *Broccoli*
Barley	Okra	▪ *Brussels*
Basil	Onion	▪ *Cabbage*
Beans, all	Peas	▪ *Cauliflower*
Capsicums	Potato	▪ *Kale*
Carrot	Pumpkin	▪ *Mustard*
Celery	Rice	Beet
Corn	Ryegrass	Spinach
Cucumber	Shallot	
Eggplant	Sorghum	
Fescue	Soybean	
Garlic	Squash	
Grasses,	Sunflower	
Herbs, all perennial	Sweet Potato	
Leek	Tomato	
Lettuce	Wheat	

VAM, like other biological products cannot be used the same as pesticides because they are living organisms. They need to be in a suitable environment and will not thrive in compacted, over-fertilised, dry or waterlogged soil or soil depleted of organic matter on microbial biodiversity (e.g. as a result of fumigation).

Biocontrol research and development is trying to answer the following questions to better understand opportunities for commercial agriculture:

1. The ecology of plant-associated microbes
   a. How are pathogens and their antagonists distributed in the environment?
   b. Under what conditions do biocontrol agents exert their suppressive capacities?
   c. How do native and introduced populations respond to different management practices? What determines successful colonization and expression of biocontrol traits?
   d. What are the components and dynamics of plant host defence induction?
2. Application of current strains/inoculant strategies
   a. Can more effective strains or strain variants be found for current applications?
   b. Will genetic engineering of microbes and plants be useful for enhancing biocontrol? How can formulations be used to enhance activities of known biocontrol agents?
3. Discovering novel strains and mechanisms of action
   a. Can previously uncharacterized microbes act as biological control agents? What other genes and gene products are involved in pathogen suppression? Which novel strain combinations work more effectively than individual agents? Which signal molecules of plant and microbial origin regulate the expression of biocontrol traits by different agents?
4. Practical integration into agricultural systems
   a. Which production systems can most benefit from biocontrol for disease management? Which biocontrol strategies best fit with other ICP/IPM system components?
   b. Can plant breeders develop effective biocontrol-cultivar combinations?

6.3.4 Biofumigation crops

Biofumigation is defined as suppression of soilborne pests and diseases by the use of plants that contain inhibitory chemicals. The plants can be harvested as rotation crops or ploughed back into the soil as green manure. Some of these crops can be used for grazing and feedstock for biogas generators.

The phase-out of methyl bromide and other fumigants under the international Montreal Protocol led to advances in the development of biopesticides (see above sections) and crops with fumigant properties. New genetics and technology make biofumigants crops an economical possibility for commercial agriculture. In addition to the fumigant activity biofumigation crops improve organic carbon and nutrient retention in soils and thus play a role in enhancing overall soil health conditions.

Plants in the mustard family, such as mustards, oil seed radish and rapeseed, sorghum species and related species, pearl millet and rocket have shown the potential as biofumigants.

Plants from the mustard family produce chemicals called glucosinates in the plant tissue. The glucosinates contained in the roots and foliage are released when it is cut or chopped, then are further broken down by the enzyme myrosinase to form isothiocyanates that behave like fumigants. These are the same chemicals that are released from metham-sodium. Brassica seed meals that are rich in glucosinolates have also been trialed as biofumigants. Sorghums produce a cyanogenic glucoside compound called Dhurrin that breaks down to release toxic cyanide when the plant tissue is damaged.

Experiences with biofumigation

The following benefits of biofumigation have been repeatedly reported:

- Improve soil physical structure by increasing soil porosity if used as green manure
- Add organic carbon to the soil which is needed to increase the activity of functional group (flora and fauna) of the soil
- Reduce weed competition and soilborne pathogens targeting a range of pathogens (broad spectrum)
- Does not persist in the soil for long because of its high volatile nature
- Change the composition of soil populations of nematodes, bacteria, and post harvest pathogenic fungi
- Alter below ground ecology, particularly the interaction between roots and microbial communities, potentially effecting associated ecosystems' processes resulting in different rates of nutrient uptake by plants

A factsheet on biofumigation crops and products for vegetables produced through the HAL project VG07125[21] is included as Appendix 6. The four page guide: “Managing soilborne diseases in vegetables” has been distributed as a package of Vegetable IPM Disease Program notes to over 300 growers at the six field days and seven national workshops conducted during the last two years of the project (2009-2010).

Work to assess the effect of these crops on specific pests, pathogens, disease complexes, weeds and nematodes in a range of production systems is ongoing.

Stephens et. al (1999) found that the incorporation of Indian mustard and canola at the same rates (of active ingredients) as methyl bromide and MS on nursery grapevines, were unable to simply replace the beneficial effects and economic returns on growth that the chemical fumigants provided.

An example from MS and biofumigation trials for the control of soilborne diseases in potatoes[22] is provided below (Box 8).

Box 8: Chemical and biological soil fumigation in potatoes

Pre-plant fumigation with metham sodium did not reduce the incidence of Black scurf, Powdery scab or Common scab, or improve the yield or quality of potatoes. Two field trials were conducted to evaluate the effect of green manure incorporation on soilborne disease and soil microbiology. Incorporation of brown mustard (Brassica juncea) resulted in a 56% reduction in Black scurf, and reduced eel worm, Powdery scab and Common scab, as well as increasing soil biological activity. In the second trial, green manure crops BQ mulch, ryecorn, lupins, ryecorn + lupins had no effect on the incidence of these diseases. Since disease overall was low, it is thought that the effect of drought masked any effect of the green manure crop. The incorporation of these plant residues, however, did increase soil active carbon and biological activity.

Grower experience in Tasmania with the biofumigant 'Caliente' prior to potatoes: "We did not use a power harrow, fertilisers or any pesticides in the following potato crop. Petiole nitrogen levels remained consistent and in the desirable range all season. Irrigation applications were reduced to six. The yield at 70 t/ha was better than that in a control area following pasture." Darren Long, MG Produce Sheffield, pers. comms.

The relationship between biofumigant crops and club root (*Plamodiophora brassicae*) disease was investigated in 2012 at Harper Adams University, UK[23]. The following biofumigants were grown in a pot experiment in soil infested with P. brassicae and incorporated: Brassica juncea (cv. Caliente 99 and cv. Vitasso), *Eruca sativa* (cv. Nemat) and *Raphanus sativus* (cv. Bento). In the pot experiment, the biofumigation process with the trial crops did not reduce club root in oilseed rape sown after the simulated biofumigation.

In general the understanding of the beneficial use of biofumigants in different production systems has increased rapidly over the past decade and reports from newer research[24]. Experiences by growers who have successfully incorporated these crops into their production systems are positive (**Box 9**).

[23] http://www.harper-adams.ac.uk/research/project.cfm?id=63

[24] Presentations at the 4th International Biofumigation and Biopesticides Symposium, Saskatoon, Saskatchewan, Canada 2011 provided an update of international R&D in the area of biofumigation. Proceedings from international conferences on biofumigation R&D are available from the International Society of Horticultural Science (ISHS). Latest research results on biofumigation will be presented at the 5th International Symposium of Biofumigation will be held at Harper Adams University, Newport, Shropshire, UK, 9-12 September 2014.

Box 9: Biofumigation crops in intensive vegetable cropping, Tasmania

"Biofumigation work began in Tasmania around 2002, where there were a number of trials assessing varieties such as BQ Mulch, and the black and white mustards, along with the initial introduction of the concept to Tasmanian growers and managers within the intensive vegetable industry. This work continued over a six-year period, whereby in 2008, Peracto (Hoong Pung) and Serve-Ag (Pete Aird) presented outcomes of their research and field-based demonstrations using these earlier varieties at an international biofumigation symposium. From this point onwards, other new varieties such as oil seed radish and white mustard varieties have also been trialled to a limited extent.

However, it is the more recent use of Caliente 199 Mustard Blend, which is reported to have much higher glucosinolate levels than all other previously trialled varieties, that is beginning to provide some very good anecdotal evidence for improved weed control, improved nitrogen levels post Caliente compared to no biofumigants, improved soil structure, excellent root penetration, increased soil organic matter/carbon, lower irrigation requirements and reportedly (by growers) less reliance on chemical usage. On the production end, the improvements to soil health are providing shortened rotations for potatoes, reduced impact on crops from pests and diseases, and increased yields. This is providing some confidence and excitement, however repeatable, quantifiable evidence, across a number of major vegetable groups, will provide local data and a better understanding as to why these results are being achieved. For instance, is the release of ITC's actually helping to control powdery scab and other diseases, or is the improved soil health enabling the plants better resistance via minimised stress?

Furthermore, we now have access to a new variety of biofumigants, 'Nemat' Arugula (Eruca sativa), a rocket that has had very little trialling so far. Similar to Caliente, this plant is also high in glucosinolates, and releases a root exudate that reportedly attracts nematodes to the upper soil profile and into the roots of that plant. Therefore, when this crop is macerated and releases ITC's, it has been reported to have had 100% kill on plant parasitic nematodes. In the USA, Nemat is planted in a mix with Caliente which is reportedly very effective."

During our consultation with carrot growers, the mustard 'Caliente' and sorghum 'Fumi8ator' were mentioned as effective biofumigation crops for carrots. 'Fumi8ator' seems to be more easily managed during incorporation than 'Caliente'. While effective, the overall performance of the biofumigation crops under high disease pressure was rated as lower than that of MS and direct costs were greater. Still, biofumigation was considered an encouraging alternative based on the lack of OH&S and environmental risks, and observed improvements in overall soil condition due to addition of organic matter.

The effective use of different biofumigation crops in different production systems and their short and longer-term economic impacts require further research on farms. The use of biofumigation/cover crops requires adjustment of the entire crop management/agronomy approach and it may take two to five years to get this right and understand overall paybacks. Potential nutritional effects on crops due to MS might have to be compensated for with adjustments to fertiliser programs when using biofumigation crops. However, several growers report that fertilser inputs can be reduced after using biofumigation crops.

Economic comparisons between pesticide and alternative management systems should consider all costs and benefits (refer to section 7).

A comparison between lettuce grown conventionally and after a biofumigation crop in the same field is shown in Figure 6-1. The size of the lettuce root system and an indication of soil health via the amount of soil adhering to the roots is illustrated in Figure 6-2.

The grower reported the following benefits for the biofumigation plot:

- Soil structure very friable and drained freely after late winter / early spring rains
- Mulched Caliente stubble easy to transplant into
- Excellent lettuce establishment
- Less ‘damping-off’ and *Sclerotinia*
- Reduction in weed bank so Kerb herbicide was not used as a pre-emergent
- Surface stubble reduced ‘wash’ after spring storm rains
- Vast root systems compared to ‘untreated’ parts of the field.

Figure 6-1: Comparison between lettuce performance without (left) and with biofumigation (right) in a trial with ‘Calienete’ at Manjimup WA

(Trial and photos by Applied Horticultural Research)

Figure 6-2: Root system of transplanted iceberg lettuce in Caliente Mustard treated soil at Manjimup approximately 50 days after transplanting, 11th December 2012 *(Trial and photos by Applied Horticultural Research)*

Biofumigation can be used as an integral part of an integrated crop protection (ICP) approach (section 6.9). Biofumigation success appears to be site and crop specific. It therefore is not a simple replacement for Metham Sodium that can be used without an initial trial and error phase and consultation with others who are using it successfully.

When using biofumigation it is important to use the right seed (type and variety), right timing (growing and incorporation) and the right way of going about it (e.g. incorporation technique, land preparation for subsequent crop). A desire to making it work and integration with other methods appears to be helping with the success of using biofumigation as an alternative to sole reliance on chemical fumigation. Growers who have gone down that path are usually interested in additional benefits of improving the overall soil health status of their land.

6.3.5 Organic amendments, biochar and 'soil or plant health enhancers'

Organic amendments and biochar

Literature reviews of R&D on organic amendments and biochar have summarised some benefits of different products for the management of soilborne diseases. Much of these can be attributed to improvements in soil biological, chemical and physical condition and associated effects on root development and function.

The scope of this report does not include yet another review of these products. Information for vegetables and horticulture in general can be found in the following research reports commissioned by Horticulture Australia:

VG99016, Compost and Vegetable Production by Bob Paulin, Kevin Wilkinson, Peter O'Malley and Tamara Flavel, DPI Victoria, published 2005.

NSW DPI has produced a fact sheet series on composts, which has been translated into many languages.[25]

AH11006, Biochar in horticulture: Prospects for the use of biochar in Australian horticulture by Justine Cox, Dr Adriana Downie, Abigail Jenkins, Mark Hickey, Rebecca Lines-Kelly, Anthea McClintock, Janine Powell, Dr Bhupinder Pal Singh, Assoc Prof Lukas Van Zwieten first published October 2012

A great number of further publications and reviews are available[26]; they can be found via Internet searches. Growers and advisers should take care that claims made in publications are scientifically and technically correct i.e. based on sound methodologies and providing objective evidence. Information from product suppliers should be checked to determine whether independent product assessments have been performed using adequate science and technology. Composts should comply with the Australian standard. The Recycled Organics Unit provides relevant information through their website at: http://www.recycledorganics.com/processing/composting/pqc/pqc.htm.

The use of organic amendments such as composts and other organic residues of plant or animal origin and biochar can be part of an integrated management approach if the effects on crop health and economics stack up. Due to the variability in products, transport distances, soils and vegetable production systems, general recommendations cannot be provided here. It is important to get representative analyses of material to be used for nutrients, carbon and potential contaminants (e.g. sodium, chloride, heavy metals, pesticide residues) and consider food safety implications. If products are high in nutrients, these must be considered in the crop nutrient budget.

'Soil or plant health enhancers'

A multitude of 'soil or plant health enhancers' is available. Many claim to have positive effects on soil conditions and plant health, mostly made by suppliers. Growers and advisers must ask for objective evidence and proper scientific and technical data to be provided if

[25] http://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/soil/compost-factsheets)
[26] Widmer T.L. et.al. 2002; Soil Organic Matter and Management of Plant-Parasitic Nematodes, Journal of Nematology 34(4):289–295.

they contemplate using any of these products. Independent advice may be valuable in many cases.

6.4 Solarisation

Solarisation, typically involves the laying of transparent plastic sheeting over flat, even beds and left in place for four to six weeks (Figure 6-3). Used with some success in California, and Israel, for example, where soil temperatures can reach 60°C at a depth of five centimetres, it is a tactic that relies on regular sunshine and also has some environmental consequences as lots of plastic is required and must be disposed of folllowing use. Solarisation is therefore not suitable for large-scale vegetable production. It may be used in greenhouses, if costs are not prohibitive.

Figure 6-3: Transparent polyethylene film applied to solarise a field on an organic vegetable farm in the San Joaquin Valley

6.5 Soil steaming

Soil steaming has been used to kill soilborne diseases in glasshouses and has proved useful at controlling weeds in field crops on a small scale. Typically, steam is applied under pressure beneath metal pans, raising soil temperatures to more than 70°C and killing most weed seeds up to a depth of 10cm. While avoiding the use of herbicides to kill weeds, soil steaming is not as environmentally friendly as one may think as it consumes a large amount of fuel and water. Work is still continuing on analysing the effects of steaming on soil life and its effectiveness against soilborne diseases. Soil steaming is not suitable for large-scale vegetable production. It may be used in greenhouses, if costs are not prohibitive.

6.6 Hydroponics

For greenhouse production, hydroponics may prove the most viable alternative to fumigation. Greenhouse production is then ideally suited to integrated crop protection.

The following information can assist in converting to soilless greenhouse production and ICP in greenhouses:

A range of R&D outputs are available to assist producers in managing pest and disease within a protected environment. These include:

- **Improving greenhouse systems and production practices** (greenhouse production practices component) (Parent - VG07096), Barbara Hall South Australia Research & Development Institute (SARDI), Project Number: VG07144
- **The Keep it CLEAN guide, Reducing costs and losses in the management of pests and diseases in the greenhouse (2009).** This is a comprehensive guide for greenhouse growers that lists and describes more than 70 management practices that can significantly reduce the costs and losses that can result from pests and diseases. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0005/442355/Keep-it-clean-booklet.pdf
- **Integrated pest management in greenhouse vegetables: information guide (2002).** This information guide is designed to meet the needs of new and existing commercial growers of greenhouse vegetable crops in Australia. It focuses on the practical aspects of IPM, and will help you to answer the most important questions about getting started with IPM and how to manage an existing program better. http://www.dpi.nsw.gov.au/aboutus/resources/bookshop/veg-ipm-info-guide
- **Converting to hydroponics** manual for growers, funded by HAL, available for purchase from SARDI as book or DVD.

A range of other R&D outputs specific to the management of pest and disease issues within a protected cropping environment can be found via InfoVeg at: http://ausveg.com.au.

6.7 Crop management

6.7.1 Nutrition management

While not an alternative to MS on its own, good soil fertility and crop nutrition management can greatly influence plants' predisposition to pests and diseases. Site-specific crop management is an integral part of integrated crop protection (ICP, section 6.9). Overall, plants with well balanced nutrient levels and no deficiencies appear to withstand pest and disease pressure better than plants that are nutritionally stressed. Good soil fertility and nutrient management should be part of an integrated management approach.

Intricacies of nutrient and pathogen or pest interactions are still not well enough understood. Interaction with diseases is better documented than interaction with pests. Plant nutrients may affect susceptibility through metabolic changes, creating favourable conditions for disease development or pest attack. When a pathogen or pest infests a plant, it alters the plant's physiology, particularly mineral nutrient uptake, assimilation, translocation, and utilization. Pathogens may immobilise nutrients in the soil or in infected tissues. They may also interfere with translocation or utilisation of nutrients, inducing nutrient deficiencies or toxicities.

Other pathogens or pests may themselves utilise nutrients or their metabolites, reducing availability to the plant and increasing the plant's susceptibility. Soilborne pathogens commonly infect plant roots, reducing the plant's ability to take up water and nutrients. The resulting deficiencies may lead to secondary infections by other pathogens. Plant diseases can also infect the plant's vascular system and impair nutrient or water translocation. Such infections can cause root starvation, wilting, and plant decline or death, even though the pathogen itself may not be very destructive.

Mineral nutrition can affect two primary resistance mechanisms:

1. The formation of mechanical barriers, primarily through the development of thicker cell walls
2. The synthesis of natural defence compounds, such as phytoalexins, antioxidants, and flavonoids.

Fungal and bacterial diseases

Thin, weak cell walls leak nutrients from within the cell to the apoplast (the space between plant cells). This can create a fertile environment that stimulates the germination of fungal spores on leaf and root surfaces. Mineral nutrient levels directly influence the amount of leakage as well as the composition of what is leaked.

Integrity and strength of cell walls and cell-to-cell connections

Potassium (K) and Calcium (Ca) play key roles in forming an effective barrier to infections. K is essential for the synthesis of proteins, starch, and cellulose in plants. Cellulose is a primary component of cell walls, and K deficiency causes cell walls to become leaky, resulting in high sugar (starch precursor) and amino acid (protein building blocks) concentrations in the leaf apoplast. Ca compounds play an essential role in the formation of healthy, stable cell walls. Adequate Ca inhibits the formation of enzymes produced by fungi and bacteria, which dissolve the middle lamella, allowing penetration and infection. Tissue that is low in Ca develops physiological disorders that cause rotting during storage.

A frequent symptom of Boron (B) deficiency is the development of "corky" tissue along leaf veins and stems because of the irregular (misshapen) cell growth that occurs. These irregular cells are more loosely bound than normal cells, producing wound like entry points for fungi and bacteria.

Most fungi invade the leaf surface by releasing enzymes, which dissolve the middle lamella that bonds adjacent cells. The activity of these enzymes is strongly inhibited by Ca, which further explains the close correlation between the Ca content of tissues and their resistance to fungal diseases.

Nutrition also affects the formation of mechanical barriers in plant tissue. As leaves age, the accumulation of silicon (Si) in the cell walls helps form a protective physical barrier to fungal penetration. Excessively high nitrogen (N) levels lower the Si content and increase susceptibility to fungal diseases.

Defence mechanisms

As stated above, plant tissues contain and produce a variety of defence compounds, which prevent fungal attacks. Boron (B) plays a key role in the synthesis of these compounds. Borate-complexing compounds trigger the enhanced formation of a number of plant defence chemicals at the site of infection. The level of these substances and their fungistatic effect decreases when the N supply is too high.

Calcium (Ca) and Boron (B) deficiencies cause a build up of sugars and amino acids in both leaf and stem tissues (in the apoplast), which lowers disease resistance.

Other micronutrients play a role in disease resistance too. Copper (Cu) is a plant nutrient that is widely used as a fungicide. The amount required as a fungicide is much higher than the nutritional requirement. The action of Cu as a fungicide relies on direct application to the plant surface and the infecting fungi. From a nutritional perspective, Cu deficiency leads to impaired defence compound production, accumulation of soluble carbohydrates, and reduced lignification (wood development), which all contribute to lower disease resistance.

Nitrogen (N) is a key component of amino acids; therefore, an excessive supply of N can bring about higher amounts of amino acids and other N-containing compounds in plant tissues. These mineral imbalances lower resistance to fungal diseases by creating a more favourable environment for them. Adequate N levels increase plant resistance to most diseases; however, excessive N can have the opposite effect. As a rule, pests and diseases that live on dying tissue or that release toxins in order to damage or kill the host plants thrive in low N situations. However, some bacteria actually increase under high N conditions. These bacteria usually depend on food sources from living tissue.

Molybdenum (Mo) deficiency can lower disease resistance by impeding the production of nitrate reductase, an enzyme that contains two molecules of Mo, and it is required to convert nitrates to proteins which are required for all plant functions.

A micronutrient-deficient plant usually has low defence capabilities against soilborne diseases. Soil-applied manganese (Mn) can inhibit the growth of certain fungi.

The use of ammonium-based fertilisers can increase the incidence of some diseases (e.g. Fusarium and Phytophthora root rots), whereas nitrate-based fertilizers generally have the opposite effect. The different N forms affect soil pH. Ammonium fertilisers generally decrease soil pH over time, particularly in soils with low buffering capacity, and nitrate fertilisers tend to either slightly increase soil pH or have no effect. However, some studies have found that the effects these two N fertiliser forms have on soilborne diseases are independent of soil pH.

Pests

Three primary pest defences of plants are:

- Physical surface properties of roots and below ground tubers or corms
- Mechanical barriers: tough fibres, silicon crystals, and lignification
- Chemical/biochemical: content of attractants, toxins, and repellents.

Mineral nutrition affects all three defence systems. Generally, young or rapidly growing plants are more likely to suffer attack by pests than older, slower-growing plants. Therefore, there is often a correlation between N applications (stimulation of growth) and pest attack. Boron deficiency reduces the resistance to pest attack in the same ways it reduces resistance to fungal infections. It is used in the synthesis of flavonoids and phenolic compounds, which are a part of the plant's biochemical defence system.

General

Relationships between plant K and diseases or pest infestations are the most frequently reported. The generalisation has been made in review literature that adequate K uptake usually results in an increased resistance to diseases and pests; K deficiencies lower this resistance.

6.7.2 Irrigation

Soil water and irrigation management can have an influence on pest and disease incidence and severity directly through providing sufficient moisture for pathogens to survive, develop and spread, and indirectly by influencing plant physiology and thus vigour and defence mechanisms. Recent research on the control of White Blister in broccoli highlights the importance of irrigation management to control diseases[27].

Important factors for soil water and irrigation management are:

- Water quality – water may contain pathogens and affect nutrient uptake
- Timing of irrigation or rain – interaction of plant wetness with other conditions conducive for infection
- Application rate and frequency – length of time plant and soil are wet and plants are stressed by wet or dry conditions.

6.8 Farm hygiene

Farm hygiene is the protection of the farming environment by preventing the introduction and/or spread of pests and diseases that may adversely affect production. Keeping farmland and equipment clean and preventing unnecessary access to production areas by other vehicles, machinery or people will help prevent the introduction of new pests to your farm. Also, keep machinery and equipment clean when moving between paddocks.

The introduction of a new pest onto your property can be a costly experience. Prevention of pest entry, or restriction of pest movement between paddocks can save much time and effort in the longer term.

Risk management information exists for vegetable growers, contractors and visitors; state departments of agriculture usually publish it with biosecurity information.

Working with a management system like Freshcare or EnviroVeg will also assist in farm hygiene management.

[27] Minchinton E. and V. Galea, 2011; Benchmarking predictive model, nutrients and irrigation for downy and powdery mildew and white blister. Final report VG07070, Horticulture Australia Limited

6.9 Integrated Crop Protection (ICP)

Integrated Crop Protection (ICP) moves away from sole reliance on fumigants and incorporates a range of methods and considerations.

ICP relies on monitoring for early detection of pests and diseases. It is based on the use of cultural methods and selective products that protect crops while minimising negative effects on water, air and soil, and on pollinators and beneficial insects. Conservation of beneficials by use of selective pesticides when pests exceed threshold levels is recommended wherever practical. Biopesticides, biological control, biofumigation and site-specific nutrition management (section 6.3-6.8) generally fit well into integrated crop protection.

ICP helps avoid pesticide resistance or enhanced biodegradation of soil applied plant protection products.

The cornerstone of an effective ICP approach is the identification and understanding of specific pathogens or pests that are causing production constraints so that targeted approaches can be implemented. This involves being able to assess the incidence and potential severity of pest and disease attacks on crops.

Unfortunately, the use and effectiveness of chemical fumigants has contributed to a lack of data or research on:

- Which pathogens or pests are mainly responsible for constraining production in different production systems and regions,
- How cultural practices influence pathogen population dynamics and severity of outbreaks, and
- Resistant or tolerant varieties, disease suppression and biological control agents (Martin 2003; McMichael 2012; Hay et. al. 2013).

Components of a more integrated system broadly include:

- Consideration of the site – temperature, rainfall, soil type
- Understanding, identifying and monitoring pathogens and pests
- Predictive tools to forecast the probable severity and economic damage potential of pest or pathogens
- Economic thresholds i.e. an understanding of how much of a pest or disease can be tolerated without economic loss
- Building and maintaining a high soil health status through increasing organic matter (amendments, biofumigation/cover crops, incorporating crop residues) reducing tillage to lessen organic matter losses and compaction, crop rotation strategies and good nutrient and irrigation management (balance, meeting crop demands).
- Crop varieties that have a higher tolerance or resistance to disease and pests
- Using healthy, strong seed and transplants that are treated against damping off pathogens (seed dressing, sprays, drenches)
- Fostering speedy, good crop establishment (e.g. sufficient phosphorus and free calcium in the rootzone, no compaction, good soil moisture management)

- Crop timing and rotation e.g. with crops that can act as biofumigants such as Brassica species; green cover crops
- Crop and farm hygiene to prevent the spread of disease
- Irrigation management to meet crop needs (minimize plant stress) and run-off/leaching prevention
- The use of beneficial organisms (biological controls) to control or suppress diseases, insect pests and weeds
- Integrating a number of non-chemical approaches, rather than relying on one or two
- Implementing a good crop-monitoring regime (soil, nutrients, irrigation, pests and diseases).

Integrated management approaches are now being more widely adopted in the EU and US In Europe, under the Directive for the Sustainable Use of Pesticides, Integrated Pest Management (IPM) is being introduced as a mandatory practice and every farmer is required to apply general principles of IPM from 2014. The Californian Department of Pesticide Regulation (CDPR, 2013) are undertaking research into genetic resistance to soil borne pests, managing and monitoring soil microbes to promote plant health, and improving production practices and protocols in an approach to develop a more integrated method of pest management.

IPM, the control of insects via integrated methods, is particularly challenging in most vegetables where the market tolerance for beneficial insects in produce is zero.

ICP case studies

The following case studies provide examples of ICP approaches for *Pythium* and *Meloidogyne* species (Root-knot nematode), both of which are known to impact carrot crops. MS has long been the conventional control mechanism for *Pythium* and Root-knot nematode.

<u>IPM for *Meloidogyne* species (Root-knot nematode)</u>

Hay et. al. (2013) advocate a rational approach to nematode management rather than using “costly fumigants and nematicides unnecessarily”. Their approach relies on understanding the lifecycle and biology of the root-knot nematode, monitoring nematode populations and implementing a range of non-chemical management strategies. Chemical treatments are used only if other methods are unsuccessful.

The main components of their recommended IPM approach are discussed beneath.

1. Understand nematode lifecycle and biology

M. arenaria, *M. javanica, M. hapla* and *M. fallax* have all been found to occur in the vegetable growing regions of WA. They are obligate parasites, obtaining their sustenance from plants and not from other soil organisms.

Eggs are laid on the surface of roots or in root tissue. Second-stage juveniles hatch from the egg and migrate in water films to find a host plant – they can move up to a meter through the soil. The nematode then moves into the root and establishes a permanent feeding site. Here it matures into an adult, which in turn lays eggs. During this phase the plant responds by developing visible gall tissue around each nematode. The lifecycle takes about 5 weeks.

The symptoms of root-knot nematodes are similar to symptoms caused by other root pathogens such as *Fusarium, Pythium, Rhizoctonia* and *Verticillium* spp. Roots need to be checked for evidence of root galling. Root knot nematodes often cause pack-out of crops due to forking and distortion.

2. Monitor nematode populations

Traditional nematode monitoring is labour intensive (e.g. manually extracting nematodes from soil and counting them under a microscope) and requires specialist skills.

In the absence of more streamlined monitoring, the recommended approach (Hay et. al. 2013) is to collect root and soil samples and forward them to an appropriate laboratory for analysis. A DNA based test is available for testing soils for a range of potato pathogens; similar DNA based testing is not commercially available for carrots or other vegetable crops. However, microscopic nematode counts have been available for a long time.

If the nematode population is high, a management plan should be devised which employs some of the non-chemical management strategies. At the end of the process, the field should be re-sampled to check the effect of the control measures.

3. Non-chemical management strategies

According to Hay et. al. (2013) root-knot nematode is a problem in the vegetable industry because:

- Susceptible crops are repeatedly sown, so high nematode populations carry over from one crop to the next; and
- Intensively cropped vegetable growing soils have a poor organic matter status resulting in poor structure and low water and nutrient holding capacities. They get easily waterlogged due to their poor structure (compaction). Natural biological control organisms have often already been eliminated or reduced through excessive tillage and application of fumigants, nematicides and other pesticides.

Improving the soil health status is critical to a successful ICP system and is the foundation of the approach prescribed by Hay et. al. (2013). The researchers recommend a range of non-chemical controls such as building and maintaining organic soil matter through organic amendments, reducing soil compaction and excessive tillage, adopting crop rotation strategies and balancing nutrient input with nutrient removal. Practice change, such as adjusting planting and harvesting dates in accordance with nematode lifecycles, and destroying infested root systems after harvest are also considered in their ICP approach.

Appendix 7 provides a list of the ICP control mechanisms prescribed by Hay et. al. (2013).

Hay et. al. (2013) emphasise the necessity of *integration* – that is, in isolation any one of the non-chemical approaches will not be successful; they need to be implemented as part of a range of control methods.

4. Possible chemical use

Hay et. al. (2013) emphasise that chemical treatments should only be employed if other non-chemical measures have proven ineffective. Possible chemical treatments include non-volatile nematicides and fumigant nematicides such as 1,3-D and 1,3D/Chloropicrin (see Section 6.2.3).

ICP for fungal diseases: *Pythium, Fusarium* and *Rhizoctonia*

A study undertaken by Minchinton et al. (2013) considered ICP strategies for *Apiaceae* vegetables, such as parsley, coriander, parsnip and carrot, that are prone to *Pythium* related diseases. Cavity spot, a soilborne disease caused by *Pythium sulcatum*, is a common disease affecting WA carrot crops. Minchinton et al. (2013) developed a set of ICP guidelines to address such diseases, the following of which are relevant to carrot crops:

- Check soil nutrient status before each crop
- Plant broccoli or other brassicas (incl. biofumigation) before *Apiaceae* crops, due to their biofumigation properties
- Maximise crop rotation periods away from *Apiaceae* vegetables to reduce carry-over of inoculum in crop debris
- Monitor four-day weather forecasts for heavy rains - to take measures, such as applying a registered or permitted fungicide to prevent mould
- Incorporate organic mulches into the soil and do not leave them not on the soil surface – this was found to enhance lateral root development in parsnips.

The IPM approaches above reiterate those prescribed by Dal Santo & Holding (2009) for the management of *Fusarium, Rhizoctonia* and *Pythium.* Effective control of these fungal diseases, which often occur as a disease complex, requires the use of all ICP management options including site selection, crop varieties, crop timing, biological options, monitoring and rouging. The addition of organic matter, in particular, has been found to be particularly effective in suppressing *Rhizoctonia* diseases (Dal Santo & Holding 2009).

Only after the suite of ICP options have been employed should the use of a fungicide be considered. Even then, Dal Santo & Holding (2009) advise that fungicides should be used appropriately and only to control, prevent, decrease or delay disease infection.

6.9.1 Levy funded IPM (ICP) strategies for Australian vegetables

Previous levy funded projects have established integrated management strategies for most vegetable crops grown in Australia to address key chronic pests and diseases. This work needs to be used when preparing extension activities (see section 8.2) and determining further RD&E needs. Key Horticulture Australia reports (available from the AUSVEG website) that summarise IPM (ICP) strategies for Australian vegetables are VG05043, VG06092 and VG09191. The summary below shows the vegetable types, for which strategies have been prepared. Corn, sweet potatoes and shallots were not included in abovementioned projects. IPM for insect pests in corn is now industry practice. MS is not used for this crop.

VG11035 provides general management strategies and recommendations for the control of soilborne diseases. These are discussed in more detail in the section 6.9.2 as they are relevant to MS replacement in all crops.

Crop	IPM (ICP) strategies available
Lettuce	2
Capsicums and chillies	2
Broccoli (brassica)	1
Beans	2
Green peas	1
Carrots	2
Pumpkins	2
Sweet corn	0
Cauliflowers	1
Cabbage (brassica)	1
Celery	3
Zucchini	1
Cucumbers	1
Sweet potatoes	0
Beetroot	1
Chinese cabbage (brassica)	1
Other Asian vegetables (brassica)	1
Fresh culinary shallots	0
Parsley	1

6.9.2 Soil borne diseases - controlling risks and management strategies

Fumigation is mainly used to control soilborne diseases and disease complexes. Therefore approaches to control these diseases are relevant for reducing the reliance on MS and moving towards ICP.

The information presented in this section has been taken from the review of soilborne disease conducted for HAL project VG11035: Review of Soilborne Disease Management in Australian Vegetable Production. Table 6-2 shows priorities by pathogen. This information highlights that the priority diseases and main host crops are nearly identical with target diseases and crops for MS use. Therefore, the discussions on how to improve the management of soilborne diseases in the VG11035 project report is relevant for reducing the reliance on MS.

Even though the industry consultation for this project happened some years ago, soilborne disease issues are expected to still be comparable. It has to be considered that the rankings in Table 6-2 are based on perceptions of growers, advisers and researchers participating in workshops and surveys and not on objective crop survey data. It is one of the weaknesses in decision-making processes in the Australian vegetable industry that for many issues objective data does not exist. However, we have to assume that growers, their agronomists and researchers recognise pest and disease issues in the field correctly and therefore provide correct information during focus group workshops, telephone interviews and Internet surveys.

Table 6-2: Soil borne disease priorities determined by industry

Soilborne Pathogen	Main crop hosts	States giving pathogen top 3 ranking (total votes)
Sclerotinia spp.	Lettuce, *Brassica* spp., beans, carrots	4 (43)
Fusarium spp.	Melons, Capsicum spp., snow peas, celery	3 (32)
Oomycetes - *Pythium* spp. *Phytophthora* spp.	Beans, peas, carrots, *Brassica* spp.	3 (28)
Rhizoctonia sp.	*Brassica* spp., cucumber, *Capsicum* spp.	1 (24)
Plasmodiophora sp. (Clubroot)	*Brassica* spp.	1 (8)
Sclerotium spp.	*Capsicum* spp., beans, eggplant, carrots, onion, garlic	0 (6)

Source: Porter *et al.* 2007

The key soilborne pathogens and their status relating to control options, detection and host range are provided in Table 6-3. This illustrates that, while integrated, cultural methods may be available; these have not been widely adopted by growers. The main reason for this non-adoption is that alternatives are often seen to be economically unviable, not practical or not reliably effective. Most pathogens are currently difficult or complex to predict (e.g. their presence and virulence) and more than half of them have a wide host range, which may influence options for rotation or break crops to break disease cycles.

One major challenge of dealing with soilborne diseases is that they often occur as disease complexes rather than single pathogens.

Table 6-3: Key soilborne pathogens and status relating to control options, detection and host range

	Chemical and non-chemical Control options[z]			Difficult to detect, predict[p]	Host range
	Lack of adoption-ready non-chemical options	Not economic or impractical	Efficacy unreliable		Widespread, multiple hosts
Sclerotinia spp.	✓	✓	✓	✓	✓
*Fusarium oxysporum f. sp. xxx**	✓	✓	✓	complex - potential	Host specific wilts
Fusarium spp.*	✓	✓	✓	complex	✓
Rhizoctonia spp.	✓	✓	✓	complex	✓
Water mould - *Pythium* spp.	✓			complex	✓
Sclerotium spp.	✓	✓	✓		
Verticillium sp.[v]	✓	✓	✓	complex	✓
Spongospora subterranea[x] (powdery scab)	✓	✓	✓	✓	Narrow - host specific
Plasmodiophora brassica[x]			✓	✓	Narrow - genus specific
Streptomyces scabiei[x] (common scab)	✓	✓	✓	✓	Narrow - host specific
Thielaviopsis basicola	✓		✓		✓
Aphanomyces sp.	✓			✓	Host specific - legumes
Clavibacter spp. (*Erwinia* spp.)	✓	✓	✓	✓	✓
Nematodes	✓		✓	complex	✓

VG11035 provided assessment summaries of biological, chemical and cultural control and risk management strategies, their opportunities and limitations. The strategies focus on ICP compatible approaches such as:

- Risk assessment, site selection (suppressive soils) and monitoring
- Climate monitoring and prediction
- Rotation (non hosts), biofumigation, green manure crops
- Hygiene (no soil movement), sanitation, clean irrigation water and weed control
- Clean, healthy seed and transplants, seed treatments
- Tolerant or resistant cultivars
- Right planting time, conditions, depths, spacing
- Promote rapid emergence and crop establishment, avoid stress on crops
- Increasing soil organic matter, maintain good soil structure (no compaction)
- Good irrigation management, no waterlogging
- Microclimate manipulation to prevent high humidity in crops
- Soilless culture, grafting
- Biopesticides and biological methods as available
- Balanced nutrition, calcium, trace elements, not too much nitrogen
- Soil pH management
- Careful use of pesticides that may cause resistance or are subject to enhanced biodegradation
- Selective pesticides in favour of broad-spectrum products.

Appendix 8 summarises key biological, cultural and chemical management options for major soilborne diseases (from VG11035). These are relevant to ICP to replace or reduce the reliance on MS.

6.9.3 Opportunities and challenges of ICP

The adoption of ICP as a potential alternative to MS presents opportunities for carrot growers and growers of other crops who currently rely on MS. ICP can create a more targeted approach to pest management and reduce costs associated with unnecessary chemical applications. It relies on assessing pests and disease risks rather than using a blanket approach. It provides a long-term management approach that is environmentally sustainable and able to withstand external changes, such as those to chemical regulation. ICP also presents an opportunity for growers to market a product that is produced in an environmentally responsible manner.

There are some challenges associated with ICP such as the availability of suitable land for crop rotation, potentially the higher labour requirements of implementing monitoring and multiple management approaches and/or costs associated with different products required in an ICP system. However, improved marketable yields and longer-term soil improvements should provide adequate financial benefits through reduced fertilser and irrigation costs, and a reduction over time in pesticide use, especially if new varieties that are disease resistant and efficient in using resources are introduced.

In order to be most effective, ICP strategies do need to be developed within a local context, in consideration of local soil types, disease pressures, and environmental conditions.

McMichael (2012) identifies this as the “know before you sow” concept which relies on understanding the **crop** x **pathogen** x **soil type** x **environment** interactions which should guide planting decisions and management options. The usual lack of adequate knowledge of these elements (as it is not needed when using MS) makes it difficult for growers to implement alternative management practices with a high degree of confidence.

The report for project VG11035 McMichael (2012) lists and discusses the following important enabling technologies for enhanced soilborne disease management. They should be considered for R&D to replace MS:

1. DNA technology – for soil microbe quantification and community composition analyses. DNA-based soil assays allow the quantification of inoculum of multiple pathogens that may be present in soil. They allow the impact of seasonal conditions, cropping sequences, biofumigant crop incorporation, enrichment treatments, anaerobic disinfestation etc. on soilborne populations, to be followed over time. It will allow soil communities and ‘suppressiveness’ to be characterised. ‘Seed’ assays using DNA technology have the potential to quantify seedborne pathogen presence, and to determine the relative contribution of seedborne and soilborne inoculum to ‘disease’ incidence. Practical use of this technology is occurring in the potato and grains industries.
2. DNA-based diagnostic and rapid screening tools - molecular diagnostics technology for multiple pathogens and nematodes; utilised also in inoculum density and reduction R&D
3. New systemic chemistry – control/protection against systemic pathogens e.g. research on efficacy and duration of seed coatings.
4. Chemical resistance and biodegradation screening. Essential component of chemical assessment that underpins regional chemical protection. Economies of scale are possible through managed, regular testing and database maintenance.
5. Genetic engineering – tools for breeding new cultivars. Gene technology includes transgenic and intragenic gene introductions, in addition to gene silencing and ‘turn-off’ technology. Newer technologies have the potential to be more readily accepted by an informed consumer than the transgenic technology has proven to be in some countries.
6. Gene technology has the potential to increase the rate of screening of genetic material (e.g. polymerase chain reaction [PCR] and sequencing technology), and to identify advantageous genes within unrelated native or resistant plants. For example, the relative influence of the environment and genetics on advantageous root or canopy architecture or fungistatic root exudates for example, may be identified more rapidly. Gene technology at present cannot however replace phenotypic screening of promising genetic material, for acceptable horticultural characteristics.
7. Precision agriculture - Guidance and GIS mapping/positioning technology
8. Precision irrigation technology – application and monitoring
9. Delivery system technology – for introducing biological control agents, hypovirulent and/or atoxigenic strains of pathogens, eg. seed coating, impregnation/infusion technology, drip- application deliveries etc.
10. iPhone applications and software platforms – for monitoring and data management; knowledge and resource updates

Some of the opportunities and challenges for ICP to replace MS are presented in Table 6-4. R&D must be participatory (growers involvement) and include assessments of costs and benefits of new approaches under commercial conditions. Extension must be focused on providing clear information in a concise format and overcoming the technical and people based barriers for change.

Table 6-4: Some opportunities and challenges of ICP to relace MS with special reference to carrot production systems

Opportunities	Challenges
▪ Foster the registration and development of biopesticides starting with products such as as Serenade® SOIL or the Biofumigant MBI-601 EP. ▪ Explore feasibility of Ethanedinitrile (EDN) ▪ Local ICP field trials designed with growers and their advisers so they have specific application to production systems and foster soil health management, reduce the risk of enhanced biodegradation and resistance development, and lower environmental and human health risks. ▪ Applied trials with biofumigation crops to understand how they can best fit with different production systems. ▪ Training of agronomists, farm advisers and growers in practical ICP, especially risk assessments (understanding of the conditions and organisms impacting on crops) and how to adapt monitoring and management strategies accordingly; use of trial sites in the training. ▪ Extension and evaluation to be integrated in R&D (participatory research using a plan-do-review-improve approach). ▪ Economic analyses to be integrated in R&D so that growers can make an informed decision about alternatives ▪ Vegetable products that can be marketed as environmentally responsible and safe (sustainable production), suitable to promote vegetable growers as leaders in that area (e.g. via EnviroVeg branding). ▪ Meet tightening international regulations and be able to capitalise on export opportunities.	▪ There currently is no single direct "drop in" chemical or non-chemical replacement for MS. Some soils have been heavily degraded through intensive cropping so that replacement of MS with ICP may require a lengthy, site-specific process and could involve initial economic losses to growers. ▪ Many alternatives e.g. biofumigation, biopesticides, organic matter increase, crop rotations work most effectively as part of a broader integrated management approach, which means a change to established production systems. This involves trial and error and thus uncertainties and risks during the time practices are adapted. ▪ ICP requires availability of suitable land and is more labour intensive. MS alternatives that have been trialled successfully on high-value crops may not be economically viable in carrot or other vegetable crops, which have lower margins. ▪ Rotational crops, such as green manure or biofumigation crops, generate no direct returns and economic benefits for subsequent cash crops are not well documented. ▪ Intensive, specialised production systems are not set up for the growing, packing and marketing of rotational crops ▪ Availability of suitable land, sandy soils and current infrastructure can limit the adoption of some alternatives. ▪ Significant work is still required to develop economically viable ICP approaches that are affordable, practical and effective in for carrots, brassicas, and capsicums, greenhouses and other production systems currently relying on MS. ▪ There will not be a 'one fits all' solution that suits all crops, growing regions and farms; while main principles will apply, local and site-specific solutions will need to be developed with growers and their advisers. ▪ A replacement of MS may, in many cases require a change in attitudes by its users or incentives.

7 Costs and benefits of alternatives

The costs and benefits of alternative methods to MS must be calculated for individual situations as options and approaches are site specific and also depend on knowledge, skills and attitudes of those who are involved in developing and ultimately using them.

As mentioned earlier, a direct ‘drop-in’ solution for MS replacement currently does not exist. A registration of Ethanedinitrile (EDN) may become such a solution while biopesticides as fumigant replacements are expected to require some adjustment of production systems.

Section 7.1 presents a comparison between using MS and a biofumigation crop. This comparison was selected because, with the exception of crop rotation, vegetable growers should adopt approaches towards ICP as part of good management practice. Long crop rotations are a challenge in intensive, specialised production systems. Many producers may not be able to change their rotations while they will be able to use biofumigation crops.

The replacement of MS with fungicides and or nematicides is not directly comparable to using MS unless the target organisms are the same e.g. only oomycetes (*Pythium*, *Phytophthora*) or only nematodes. If fungicides plus nematicides needed to be used in a program with pre- and post-emergent herbicides, cost would be much higher than the expenditure for just MS.

When comparing direct treatment costs and benefits the ‘real costs’ of MS and alternatives remains unknown because it is hard to place a value on some effects, especially longer-term ones, and potential consequences for the environment and people remain unaccounted for.

7.1 Metham Sodium vs biofumigation

Metham sodium $500/ha		**Biofumigant $900-1100/ha**	
Benefits	**Risks**	**Benefits**	**Risks**
Broad spectrum	Enhanced biodegradation	Broad spectrum	Efficacy depends on type and conditions
Known method	Long term reduction in soil life	Improvement in soil life and disease suppression potential	Still unknown to many growers, needs development
Relatively easy to use	OH&S issues may occur	Increase in soil organic carbon (OC) $500-1000? [1]	May need to be combined with other changes in practices
Recommended by many advisers	Leaching through rootzone possible – reduced efficacy	Improved soil structure, nutrient and water holding capacity (included in OC benefits)	Advisers have little experience with it
Low stress level / perceived certainty of success	Off site effects $ not accounted for	Off site benefits[2] $ not accounted for	Potential uncertainty of success is stressful
		OH&S less of an issue	

[1] Currently, soil carbon may be valued at $20/t, however, when just looking at humus, of which carbon was the main component, and valued the nutrients and water typically held within a kilogram of humus, the value of OC would be around $300/t on today's prices.

If there is 1% OC over 30 cm soil depth, the amount of OC stored over 1 hectare of land can weigh about 42 tonnes. Given the above values, 42t of OC would be worth $ 12,600 at $300/t or $ or only $840 at $20/t.

[2] This does not include organic carbon benefits from the fact soils with higher levels of organic carbon are more resistant to erosion, are more resilient and usually require less inputs (fertilisers, pesticides, water); they also deliver less pollution to waterways, biodegrade pollutants and buffer climatic extremes.

The use of a biofumigant crop compared to using MS would on average cost about twice as much for product and application vs seed, planting and incorporation. The costs of both 'treatments' would have to be weighed against the benefits and risks as per above table.

7.2 Economic analysis tool

Currently it is difficult to provide solid, defendable dollar values on long term or triple bottom line costs and benefits of different options to control soilborne diseases and weeds, the targets of MS. Usually economic imperatives **and** attitudes of individual farm business owners influence final crop management decisions. The knowledge about alternatives and personal perceptions of risks play a part in these decisions. It is one of the challenges of extension to make sure growers have a good understanding of alternative technologies and risks as well as opportunities for the business, people and the environment. The availability of a suitable economic analysis tool can greatly help with extension of alternatives to MS because they are usually considered more expensive than the fumigant.

The HAL project VG12048 (Plant Health Desk Top Study, 2013) produced an economic analysis tool that allows comparing the benefits of different management approaches for a business or the industry. This tool should be used to assess differences between use of Metham Sodium and alternative management approaches. The tool is based on gross margins and therefore fixed costs are not included. In the tool, gross margins compare direct costs for one season. This means that longer-term effects of MS and alternative methods as well as potential costs relating to impacts on people or the environment including soil health are not reflected up by the model.

The model could be reviewed so that it can be used to reflect costs/benefits for a crop rotation rather than one crop.

8 Research, Development and Extension

8.1 Research and development (R&D)

The reliance on chemical soil fumigants, such as MS, continues in the absence of alternatives that provide growers with the same level of 'security' and returns. A change in the registration status or market pressures (MRLs, market acceptance) could result in the need to effectively use alternative methods. R&D and extension will assist in being ready for a change by determining effective alternatives that suit local soil types, disease pressures and environmental conditions.

According to Martin (2003), McMichael (2012) and Hay et. al. (2013), future R&D in the area of soilborne pests and diseases should focus on:

- Building knowledge of soilborne pathogens for growers and their advisers e.g. the biology, the response to the presence or absence of a host, the host range, environmental influences on the host, the pathogen and their interactions
- Effectively testing soils for the presence of pests and diseases and the likelihood of attack (economic and biological thresholds)
- Providing clarification of pathogen complexes that are leading to reduction in yield
- Understanding how soil type, health, physical and chemical structure influence the impact of soilborne pathogens, and of those introduced to the soil e.g. on planting material
- Establishing integrated management options for different pests, diseases and conditions
- Testing for biodegradation of MS, metalaxyl and other soil applied products
- Breeding strategies to enhance crop tolerance or resistance to diseases
- Determining the economic viability and benefits of alternative practices and treatments required for managing pest and disease risks; this needs to include longer-term viability and the real costs and benefits of MS and its alternative management options.

Demonstration trials will be required for extension purposes, R&D trials will be required to provide scientific data on the efficacy of alternative treatments against identified, target pathogens, whether chemical or non-chemical. Efficacy and/or residue trials will be required for chemical alternatives, if APVMA registration was required.

Local, on-farm and participatory R&D field trials provide an opportunity to:

- Increase the understanding and identification of specific pathogens and diseases that are impacting carrot and other vegetable crops so that targeted, integrated approaches can be developed
- Trial cover crops that can be used in short windows between crops and assist in building soil carbon, soil life, nutrient cycling and soil structural stability
- Understand the effectiveness of biofumigants, organic amendments and other practices in managing soil pathogens and pests diseases in different production systems
- Determine the economic viability of all alternatives trialled

- Determine the most effective and economic application methods or combination of alternatives.

In addition to trialling MS alternatives, an improved understanding of enhanced biodegradation of MS is required. A survey of the incidence and levels of enhanced biodegradation across farms with long-term MS use would reveal the extent of this issue and assist in on-farm decision-making about the continued use of MS as an 'effective' product.

The main aim of any further work on soilborne disease management and MS replacement must provide vegetable growers with a way to make risk based decisions and have a range of practical management options available. Growers and their advisers must understand the advantages, disadvantages and real costs of MS and management alternatives (Box 10).

Box 10: Important aspects of on-farm RD&E trials

- R&D trials need to occur regionally and have relevant outcomes for production systems in the region
- Establish the interest and support of local growers who are willing to participate in trials and have others visiting their farm e.g. for field days
- Requirements, risks and rewards of being involved in trials need to be clearly communicated to the participating growers
- Growers need to be involved in the design of trials to make sure they are feasible for implementation on farm
- Trials need to occur in a relatively controlled environment and/or involve collecting data on all influencing factors; they need to be run over several locations
- Trials need to be observable and results understandable
- Trials need to occur over a long timeframe e.g. 4 – 5 years in order to properly determine the effectiveness and economic viability of alternatives
- Progress and outcomes of the trials need to be regularly communicated to other growers and industry in an inclusive and practical way
- Economic data must to be collected as part of each trial
- Uptake for trial results by growers need to be monitored and feedback from growers must be included in new trials.

8.2 Extension

Our research highlighted that the drivers for MS use differ in each crop and region, i.e. the initial target organisms and reasons for continued use of the product are not the same. Therefore one-for-all, written extension products (factsheet, PowerPoint presentation, emails newsletter) will most likely not be effective in enticing growers to explore and use alternatives, especially if they involve new technologies and approaches.

Non-chemical alternatives are site-specific, complex and can involve perceived or actual risks. The complexity means that before growers can change practices they need to have the opportunity to investigate alternatives in their region and/or on their farm. For this to happen technical guidance is usually required and this would best be provided by a known and trusted person.

8.2.1 Communication of R&D as it happens

R&D trials should be underpinned by effective communication and targeted extension material and services to increase grower confidence and understanding of MS alternatives.

A recent study prepared for HAL (Blaesing et. al. 2013) detailed the following communication recommendations, which have application to this project:

- Focusing on better communication of outcomes to growers (projects should comprise at least 30 – 40% of the budget for extension, with extension specialists part of the system)
- Ensuring research programs include an extension component which involves/informs all sectors of the industry (this includes service providers such as agronomists, advisers and crop protection product producer / supplier representatives who have regular contact with vegetable producers). Due to the diminished capacity of government extension services, private industry will be the main conduit of information to growers and need to be better incorporated into the R&D loop to ensure relevant information gets out to growers
- Embracing new communication technology (social media, internet, smart phones, apps) to assist with the dissemination of research results and ensuring that on-line resources remain updated and relevant
- Including information on the economic impact of various crop health management options so that producers are aware of how implementation will affect profit margins within their business.

8.2.2 Safe use of Metham Sodium

An important part of an extension program will be to initially provide vegetable growers who rely on MS information that helps them to use the product safely with minimum impacts for human and environmental health. MS users need to understand limitations to its usage and efficacy (e.g. enhanced biodegradation). The Nufarm MS stewardship program provides a good example of providing useful information. Nufarm is the only supplier of MS who has taken this step. An approach similar to the US EPA fumigation toolbox (http://www.epa.gov/pesticides/reregistration/soil_fumigants/) should be considered to further assist growers.

8.2.3 Reducing the reliance on Metham Sodium

The primary purpose of extension to reduce the reliance on MS in vegetable production systems, especially carrots, is to deliver a planned and supported approach over a number of years using existing extension paths and targeted approaches.

Tailored extension presents an opportunity to build grower understanding and confidence of suitable alternatives to MS and generate long-term practice change. McMichael (2012) suggests that the plethora of information available on soilborne diseases makes it difficult for growers to "synthesise the components relevant for their specific production systems and current disease threat". Continued use of MS is one response to the complexity and uncertainty about how suitable alternatives alone or in combination may work on 'my farm'. MS is the 'known' fall back position in spite of its disadvantages (human and environmental health risks, enhanced biodegradation, potential leaching). Therefore an extension program must deliver straightforward messages about practical proven solutions.

Extension materials, programs and services must be specific to local growing conditions and to the needs of growers in the region. It is recommended that activities be supported in relation to (Blaesing et. al. 2013):

- Providing coordinated extension programs and services for growers and advisers on existing information as a matter of priority and as integral part of new R&D projects
- Use of regional demonstration sites on farms
- Use of crop or regional champions who have already implemented new technologies (and rewarding them)
- Utilisation of existing knowledge products and resources (e.g. the US fumigation toolkit, R&D outputs from biofumigation research, soil biology R&D outputs)
- Utilisation of existing integrated management extension resources and platforms such as EnviroVeg, Landcare
- Initiating commercialisation of new technologies from R&D so they become available as services or products to growers (e.g. soil testing for pathogens or biodegradation, new biocides or fumigation products).

Extension cannot rely on improved communication alone to provide a bridge between science and industry to facilitate change. One important aspect is building capacity for growers and advisers to access a wide range of practical resources and tools and make well-informed decisions. The development of a self-assessment tool and options guide for key production systems that rely on MS could be one tool to convey alternative methods and encourage their use.

Demonstration of alternative methods in key regions would go a long way towards enticing growers to explore options on their own farm. These types of demonstrations are planned for two recently commissioned projects for the vegetable industry. These are VG13071 Soil Condition Management and Capacity Building and VG13078 Extension of Integrated Crop Protection. Reducing the use of MS could fit well within either of these projects; i.e. additional demonstration sites and/or field days may be integrated into one or both projects.

8.2.4 Extension paths

Capitalising on existing programs

There is opportunity to capitalise on existing extension programs and resources to deliver effective R&D trials and communication activities. This provides multiple benefits i.e. cost and time efficiencies, an opportunity to reinforce the messages of the existing programs and allowing access to an already engaged audience.

There is potential to use existing programs such as EnviroVeg to support vegetable and especially carrot growers in transitioning to more integrated management practices. EnviroVeg provides growers with the ability to benchmark activities against those of other growers, provide an environmentally responsible product and have the advantage of communicating to industry and supply chains that they are caring for the environment (AUSVEG 2013a).

Established communication tools, such as InfoVeg grower discussion groups and trusted advisers, can assist in the dissemination of information to growers. Approaching discussion groups can be a useful mechanism to access growers in order to generate interest and support for on-farm R&D and demonstration trials.

The previously mentioned HAL extension projects (Integrated Crop Protection (ICP) and the Soil Condition extension and capacity building) currently do not specifically consider alternatives to MS. However, they provide an opportunity to reiterate the messages of ICP and soil condition management to growers, especially where chemical reliance and diseases issues are high and alternatives to MS have not yet been considered.

Table 8-1 provides an overview of existing programs that can provide conduits for the extension of alternatives to a reliance on MS.

Table 8-1: Existing programs, resources and communication tools

Program /Resources	Description
EnviroVeg	An industry led environmental program for Australian vegetable growers. All growers subscribing to the program receive a free EnviroVeg manual, newsletters and invitations to special training events. A basic self-assessment program is offered free to all National Vegetable Levy paying growers. Growers can progress through the program once they have submitted a minimum of one self-assessment and achieved a score of 85% or greater as well as an Environmental Action Plan to AUSVEG. Participation in the self-assessment allows growers to benchmark themselves against others. Growers will be able to display an EnviroVeg logo at the gate. Moving to higher levels requires the grower to prepare their operation for potential third party audits.

Program /Resources	**Description**
EnviroVeg Platinum (EnviroVeg Stewardship Scheme)	A recently launched extension of the EnviroVeg Program. Growers seeking additional recognition for their practices are able to have their practices verified by an independent party and can access new rewards under the scheme. The EnviroVeg coordinator supports growers in preparing for audits. Growers are still required to complete and submit a self-audit and self-assessment annually to AUSVEG. The grower meets audit costs. In return, growers received increased recognition of their environmental performance and access to rewards such as use of the EnviroVeg logo in their business and on packaging.
InfoVeg	A web-based application, administered by AUSVEG, allowing growers access to all levy funded vegetable-related R&D information in a range of formats from over 10 years of research. The application is aimed at assisting growers and their advisers to better understand consumers, develop new markets for their produce and increase the productivity of their operations. It bridges the gap between research and growers.
Good Practice Guides, Factsheets, Resources and Tools	State based vegetable growers associations and departments of agriculture / primary industries provide Good Practice Guides, Factsheets and R&D reports on topics including nutrients, water, pest and disease, biodiversity and soil management. Economic analysis tools are also available. The resources provide useful guides for the establishment of integrated management systems. They can be accessed via: http://www.vegetableswa.com.au/goodpractice.asp www.agric.wa.gov.au/ http://www.vgavic.org.au/ www.depi.vic.gov.au www.sardi.sa.gov.au/ www.pir.sa.gov.au/ www.growcom.com.au/ www.daff.qld.gov.au/ www.dpi.nsw.gov.au/ (http://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/soil) www.nswfarmers.org.au/ www.tfga.com.au/ www.tia.tas.edu.au/
VG13071 Soil Condition Management and Capacity Building and	Potential to help demonstrate and reinforce the importance of soil condition management for the control of soil borne diseases and pests, especially in production systems with high MS use.
VG13078 Extension of Integrated Crop Protection	Potential to help demonstrate and reinforce ICP alternatives especially in production systems with high MS use.
Discussion groups	Existing grower discussion groups can be identified or groups formed to be best practice ‘champions’ in the development of alternatives to reliance on MS.

Tailored activities

In addition to using and building on existing extension programs and resources, it will also be necessary to develop tailored extension activities, which are orientated specifically towards achieving the objectives of reinforcing safe practices and developing alternatives to MS to provide long term sustainability of production systems.

As mentioned above, locally relevant RD&E field trials/demonstrations and communication will be necessary to develop regionally appropriate, effective MS alternatives. Targeted workshops and discussion groups with growers, advisers and industry representatives could assist in generating interest and support for local RD&E trials and communicating the progress and outcomes of trials. Discussion groups but also other local forums can be helpful in supporting growers to transition away from MS, especially if they are not a one-off event, and participants can develop relationships with each other and the facilitator(s).

Practical tools and resources (‘knowledge packages’) can be used to support growers in developing their own alternative pest management strategies. Australian vegetable growers highlighted that practical knowledge packages especially as those listed in Box 11 would be beneficial for them (McMichael, 2012). They should focus on ‘adoption-ready’ knowledge rather than ‘early innovation’ information that cannot be implemented with any confidence.

Box 11: Content of practical knowledge packages (adapted from McMichael, 2012)

- Risk factors associated with significant pathogens affecting vegetable crops, and how they can be assessed (field and laboratory assessments) and managed in regional or individual farm production systems, risk include enhanced biodegradation and resistance
- The economics of different management options such as inoculum reduction and pest and disease avoidance or suppression measures and other integrated MS alternatives

Communications must use clear, concise, consistent messages and involve trusted advisers and information sources in delivering information.

8.2.5 Planning extension activities

The delivery of extension activities requires a planned and coordinated approach. The report VG12048 (Blaesing et al 2013) includes a section on principles of extension for different grower groupings and effective approaches; this information should be used when designing extension for the replacement of MS.

The first step in the extension pathway should be to increase the knowledge and skills of growers and their advisers about soilborne pests and diseases, risk assessment, management opportunities and potential economic impacts of different approaches, as well as timeframes required to ‘turn things around’ if high disease pressure is a result of declining soil conditions.

Attitudes and aspirations may have to be addressed at the same time based on an understanding of the drivers for MS use in different production systems.

A second step for an extension program should then be to foster and support practice change over time based on R&D outcomes.

In consideration of earlier discussions, the following steps are proposed to integrate knowledge and disseminate it in a way that allows growers to try and adopt practices that can reduce their reliance on MS:

1. Identify the overall goal of the extension program(s)
2. Determine specific outcomes and impacts to be achieved over time (outcome continuum)
3. Determine the outputs (activities, approaches, tailored knowledge packages, tools, events etc. and participation) required to achieve each outcome step
4. Describe inputs (resources such as people, materials, equipment etc. and budget) required for each output
5. Record assumptions made in preparing steps 1-4 and external factors that may influence success
6. Identify resources and gaps (R&D needs)

Table 8-2 provides a high-level extension plan logic addressing the above points.

The next step would be to use this plan to prepare specific implementation work plans for targeted delivery considering regional differences in current practices and pests and diseases, as well as grower knowledge, skills, attitudes and aspirations.

8.2.6 Extension to the carrot industry

The report for HRDC Project VG98051, Technology Transfer to the Australian Carrot Industry, includes information on drivers and barriers for adoption of new technologies in the carrot industry. Even though the study was conducted many years ago, most of the issues discussed then still apply, especially as many of the growers interviewed for the report are still active in the industry today.

Therefore, this report can be a useful reference for the design of extension programs for the carrot industry. It includes information on what carrot growers value in extension programs, how they would like to access information and attributes of effective extension personnel.

8.3 Extension products

This project produced two extension products:

1. A factsheet, which is included as Appendix 9
2. A PowerPoint presentation, which is included as Appendix 10.

These summaries are designed to provide an overview of issues and solutions and encourage growers and advisers to seek further information from this report and other sources such as EnviroVeg, InfoVeg, VG13076 - Soil condition extension and capacity building and VG13078 - Integrated Crop Protection extension.

Table 8-2: High-level extension plan logic as a basis for specific work plans

<table>
<tr><td colspan="3">Extension Plan: Alternatives to Metham Sodium (MS)</td><td colspan="3">Plan Number: TBA</td></tr>
<tr><td colspan="6">Overall Goal: Reduce the reliance of vegetable growers, especially those growing carrots on fumigation with Metham Sodium to control soilborne diseases and weeds.</td></tr>
<tr><td colspan="6">Situation: Metham Sodium is used in intensive, specialised production systems to control a range of pests and diseases and fulfil the market demand for 'good-looking' vegetables. For most MS users, the product is considered an essential, affordable management tool. Still, growers want to be proactive in developing alternatives for the case MS becomes more strictly regulated as happened in other countries. Some are concerned about it's toxicity and long-term efficacy (enhanced biodegradation).</td></tr>
<tr><td colspan="6">Specific Focus/ Needs: For regional / crop specific extension plans, first understand drivers for MS use in that region and for that crop and the target organisms; consider this in a detailed extension plan.</td></tr>
<tr><td>Target organisms:</td><td colspan="5">Soil borne diseases, insects, nematodes, weeds</td></tr>
<tr><td colspan="3">OUTCOMES / IMPACTS (timelines may differ for these, they may be added here)</td><td colspan="2">OUTPUTS</td><td>INPUTS</td></tr>
<tr><td>Long-term results</td><td>Intermediate results</td><td>Short-term results</td><td>Participation</td><td>Approaches (leading to methodology, activities)</td><td>Requirements / provisos</td></tr>
<tr><td>Changed Conditions /Project Legacy (Lasting improvements / progress)</td><td>Practice Change / Technology Use</td><td>Change in learning, understanding, technology development</td><td>Reach, (Who will be involved, trained, engaged, informed?)</td><td>Approaches leading to activities (in work plan) aimed at achieving outcomes</td><td>Resources / information / people</td></tr>
<tr><td>No off site effects or effects on humans from MS use (stewardship program)</td><td>Growers use MS as a last resort and 'by the book'</td><td rowspan="7">Awareness, Knowledge, Attitudes Skills, Aspirations, Motivations have changed so that stewardship programs and alternative plant and soil health management methods are considered and tried.</td><td rowspan="7">Farm owners & farm managers
Agronomists, advisers, consultants
Department & other extension providers
CMA's, NRMs and others with an interest in sustainability
Researchers
Technology companies</td><td>MS Stewardship workshops and booklet as a first point of engagement</td><td rowspan="7">Funds (VC, Levy, HAL etc.)
Research findings,
Experience, know how
Technologies, resources, tools
Networking between extension providers and programs
Grower champions
Demo / Reference sites</td></tr>
<tr><td>Reduction in the use of soil fumigation and increase in the adoption of integrated management methods</td><td>Growers work towards integrated management that suits their farm</td><td>Demonstration trials on farms, field days, discussion groups</td></tr>
<tr><td>No marketable yield losses due to pests, weeds and diseases or decrease in profit margins when alternative management approaches to MS are used</td><td>Good soil, nutrient and water management, and rotation/cover & biofumigation crops help in reducing pest and disease pressure and improving marketable yield</td><td>Entice growers to participate in extension programs and use best practice information aimed at ICP and improving soil condition</td></tr>
<tr><td>No decrease in profit margins when alternative management approaches to MS are used</td><td>Decision making and economic assessments consider all costs and benefits of pest and disease control methods using an appropriate tool / calculator</td><td>Provision of and training in the use of economic analysis tools that allow an economic assessment of alternative approaches</td></tr>
<tr><td>Improved market access, promotion of sustainable practices (e.g. EnviroVeg Platinum)</td><td>Domestic markets reward 'sustainable production', supply to export markets has increased</td><td>Assist all growers using MS to participate in the EnviroVeg Platinum program</td></tr>
<tr><td>Use of resistant varieties (to MS target organism)</td><td>Resistant varieties are tried and used</td><td>Provide information on varieties and their agronomy</td></tr>
<tr><td>Predictive and monitoring tools for MS target organisms are used</td><td>Risk assessment and monitoring are used</td><td></td></tr>
<tr><td colspan="6">Planned risk management and assessment / Review of OUTCOMES/IMPACTS at key stages of the work plan and roll out to allow continuous improvement of the extension program (adaptive management).</td></tr>
<tr><td colspan="3">Assumptions</td><td colspan="3">External and Internal (or Systems based) Factors or Issues</td></tr>
<tr><td colspan="3">Availability / capacity of resources, R&D to underpin the program, tools and people</td><td colspan="3">Positive and negative attitudes about what can be achieved</td></tr>
<tr><td colspan="3">Economic and crop health benefits of alternatives are known (reliable data available), if not, this needs to be part of the RD&E to be conducted</td><td colspan="3">Changes in the regulatory status of MS or market acceptance issues (MS, alternatives, look of vegetables)</td></tr>
<tr><td>References / Resources</td><td colspan="5">Refer to VG 13045, references and resources listed there and others available to support knowledge and practice change.</td></tr>
</table>

9 Synthesis and recommendations

This section assimilates findings from the study and outlines recommendations.

Effective extension will be vital for the economically sustainable use of MS, protecting people and the environment, and especially for the adoption of alternative management methods. R&D is required to fill knowledge gaps on disease complexes, disease risk prediction and production economics.

Extension needs to focus on:

1. Improving the safe use of Metham Sodium using existing resources and tools from Australia and overseas, and available, effective extension pathways
2. Improving site-specific management capabilities for soil and crop health through improving the understanding of integrated management options of growers and their advisers; this should be done via applying the large amount of plant and soil health research that has been conducted for the vegetable industry, and relevant information from other industries (GRDC, Cotton), in Australia and applicable overseas information
3. Local demonstration trials and practical training targeting regional needs
4. Integrating economic aspects with extension of all technical information.

9.1 Vegetable Production Systems

Extension should be prioritised to assist growers producing crops on a large area nationally, and relying on MS to do so e.g. carrots, brassica vegetables, capsicums and lettuce. Growers of other crops will be able to learn from supported approaches taken in these major crops. Carrots should be targeted specifically because reducing MS use may be required to gain access to new markets. Carrots, a major crop by area and value, also appear to be the crop with major MS inputs.

Existing extension programs in the area of soil health, integrated crop protection and environmentally sustainable production (e.g. EnviroVeg) should be used as initial extension pathways if feasible. Trusted advisers to growers and other regional key influencers should be engaged and kept informed as a matter of priority.

In most cases, the target crop, e.g. carrots, is grown in rotation with other vegetable crops, potatoes or pasture. Therefore MS replacement approaches must fit into a rotation.

A stewardship approach and risk based decision-making tools should be made available for vegetable growers. These could build on the Nufarm Metham Sodium Guide for Australian growers, the US EPA ‘fumigation toolbox’ and self assessments e.g. as used in the EnviroVeg program.

9.2 Business Implications

Business implications of MS replacement need to be clearly identified for growers, especially for the main crops relying on MS. This needs to include a longer-term and wider view than just the comparison of annual treatment costs and consideration of returns for the marketable yield of one crop (annual crop gross margins). Rotations, health and environmental benefits should be considered.

It may be desirable to use information on markets and consumers to find out whether the 'glossy finish' achieved via MS is essential. At the same time growers need to know how and how much the alleged increasing demand for 'chemical free' vegetables could really affect them.

9.3 Data and Information Management

Foundation data and information

While estimates of the total market size and thus use of MS are available, reliable hard data on its use and intensity in different crops and regions is not available. This means that the risks of MS use cannot be judged properly and extension and R&D efforts have to be based on assumptions rather than data. We also do not understand which organisms must be or are controlled by MS. Growers have usually commenced using the product to control a specific pest or disease and have continued to do so based on broad spectrum efficacy and to manage multiple disease risks without knowing whether they are a threat and how large this threat is.

It may be possible to source data via MS supply chains and work with suppliers of MS to improve data and safety, e.g. where MS is being purchased in large quantities, follow up use with grower. N.B.: MS cannot be stored for long periods because it will crystallise. Therefore if a grower purchases large quantities it can be assumed that it is for immediate use.

Knowledge resources and tools

Information on alternative chemical and non-chemical options and good management practices should be made available e.g. as part of the abovementioned 'toolbox' (one-stop-shop). They could be included on the EnviroVeg manual and website or as part of InfoVeg.

9.4 Good decision making/training

Extension and R&D activities must focus on improving growers' and advisers' capacity to make good decisions. They require good information and data about their production/crop management systems and business implications of using MS or alternatives.

Many vegetable growers would benefit from a better understanding of soil and plant health interactions, management options, business management principles and technologies to be able to fully use information resources and decision tools for their farm.

9.5 R&D

Research to fill knowledge gaps on pests and diseases, and especially disease complexes currently controlled with MS should follow the integrated plant health and crop protection RD&E framework and strategies presented in VG12048.

R&D on alternative management approaches or products should:

- Occur over a timeframe of at least three growing cycles

- Occur in a known (adequate data collection on influencing factors) or controlled environment and over several locations in the same crop
- Focus on alternatives that have a low environmental and human health impact and would not be prone to resistance development or enhanced biodegradation
- Adequately consider the longer-term economic viability of MS and alternatives by adequately accounting for all costs and benefits.

General R&D priorities are:

1. Registration of alternative pesticides (e.g. through collaboration with chemical manufacturers) with a lower environmental and human health impact (than MS) that are registered in other countries e.g. US and Germany for the control of soilborne diseases or as fumigants (discussed as alternatives in this report)
2. Access to and or development and registration of biocide products
3. Biocontrol technologies; especially the integration into vegetable production systems
4. Developing diagnostic tools (e.g. DNA testing) that allow growers to understand risks of marketable yield losses due to specific pests and diseases, which they usually aim to control with MS in an 'all-in-one' approach
5. Identifying where MS is subjected to enhanced biodegradation or resistance so that growers do not waste money on ineffective treatments, focus on where MS is used frequently
6. Understanding disease complexes especially their development and impact, including thresholds, in intensifying production systems
7. Applied R&D on the practical use of integrated methods, especially biofumigation, in major vegetable production systems that currently rely on MS; this must build on previous work and include economic assessments of alternatives (business implications) with due consideration of longer term and triple bottom line costs and benefits (Profit, People, Planet)
8. Participatory, applied R&D (involvement of growers and their advisers) and extension of practical results and related economic information throughout R&D projects
9. Improving data collection on pest and disease issues so that RD&E can be directed towards issues with the greatest economic impact
10. Updating the economic analysis tool from VG12048 so that longer-term cost and benefits can be estimated
11. Understanding the real cost of the impact on the environment and human health from continued use of MS.

9.6 Extension

Communication summaries for the start and end of the project have been provided to AusVeg. A factsheet (Appendix 9) and a PowerPoint presentation (Appendix 10) on alternatives to MS have also been developed. These products will encourage vegetable growers to move towards an integrated crop protection approach and seek further information from this report and their advisers.

References

References are also included as footnotes throughout the report.

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Appendix 1: EU Directive 91/414/EEC authorisations for plant protection products, Annex 1 - essential use permits (Council of the EU 2009)

28.7.2009 EN Official Journal of the European Union L 196/25

ANNEX

List of authorisations referred to in Article 3(2)

Column A	Column B
Member State	Use Soil disinfection and weed control before planting/sowing, limited to professional users with appropriate protective equipment under specific authorised conditions as laid down in Article 3 and subject to the following restrictions per Member State:
Belgium	Potting Soil (all crops). Potatoes (seed, ware and starch potatoes), sugar and fodder beets, onions, vegetables, fruit crops, herbs, orchards (replanting), ornamentals.
Bulgaria	Glasshouse use: tomatoes, cucumbers, lettuce, carrots, peppers, aubergines and tobacco.
Cyprus	Nurseries, vegetables, potatoes, ornamentals, deciduous fruits, citrus fruits, and grapes.
France	Vegetable and fruit crops and mainly lamb's lettuce, carrots, tomatoes, strawberries, asparagus, ornamental plants, trees and shrubs.
Greece	Potting soil and soil compost (for all crops), indoor and outdoor use for soil treatment (for vegetable and ornamental crops), tobacco nurseries.
Hungary	Field use: potatoes, carrots, celeriac, parsley root, ornamentals, berries, apples, pears, tobacco, wine grapes, stone fruits, fruit and grapevine nurseries. Glasshouse use: green peppers, tomatoes, cucumbers, carrots, celeriac, parsley root, tobacco, berries, ornamentals.
Italy	Rice, lettuce and similar, tomatoes, peppers and aubergines, cucurbits, carrots, bulb vegetables, stem vegetables, potatoes, tobacco, replanting vineyards and orchards, flowers.
Ireland	Glasshouse use: tomatoes, carnations, cucumbers, ornamentals, chrysanthemum and lettuce. Field use: potatoes, bulbs, hardy nursery stock, cane fruit, turf, strawberries and forestry plantations.
Malta	tomatoes, aubergines, peppers, melons, watermelons, squash, cucumbers and strawberries.
The Netherlands	Potatoes (seed, ware and starch potatoes), sugar and fodder beets, onions, vegetables, strawberries, orchards (replanting), ornamentals (including growing of bulbs), yellow nutsedge in all crops.
Poland	Field use: strawberries, cabbages, carrots, lettuce, onions, garlic. Glasshouse use: tomatoes, cucumbers, peppers, aubergines.
Portugal	Potatoes, onions, carrots, melons, strawberries, cucumbers, peppers, tomatoes, citrus crops, ornamentals, glasshouse soil fumigation, nursery soil fumigation.

Appendix 1 continued

L 196/26 EN Official Journal of the European Union 28.7.2009

Column A	Column B
Member State	Use Soil disinfection and weed control before planting/sowing, limited to professional users with appropriate protective equipment under specific authorised conditions as laid down in Article 3 and subject to the following restrictions per Member State:
Romania	Vegetables and ornamental plants.
Spain	Nurseries, seedbeds, vegetables, tobacco, flowers, strawberries, seed potatoes, vineyards.
United Kingdom	Glasshouse soils, nursery soils, outdoor soils and potting soils prior to planting of fruit crops, vegetable crops, potatoes, herbs, flowers, bulbs, ornamental plants, perennial plants.

Appendix 2: Metham Sodium toxicity assessment (Cox 2006)

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● **F U M I G A N T   F A C T S H E E T**

METAM SODIUM

Metam sodium is the most widely used soil fumigant, and the third most widely used pesticide in U.S. agriculture. Half of its use is in potato production, and 90 percent of its use is in Idaho, Washington, Oregon, and California.

Metam sodium acts as a fumigant by breaking down into methylisothiocyanate (MITC).

Symptoms of metam sodium poisoning in exposed people include burns, eye irritation, difficulty breathing, nausea, diarrhea, anxiety, and blurry vision. Poisonings have occurred as far as a mile from the application site.

In laboratory animals, metam sodium caused a wide variety of health effects. These include a reduction in the activity of immune system cells, a reduction in the levels of the hormone that triggers ovulation, a reduction in leg strength, a reduction in activity, anemia, damage to the lungs, and damage to the liver.

Both the U.S. Environmental Protection Agency (EPA) and the California EPA classify metam sodium as a carcinogen (a compound that causes cancer). These classifications are based on laboratory studies in which metam sodium exposure caused malignant tumors. California EPA also classifies metam sodium as a reproductive toxicant because it has caused pregnancy loss in laboratory studies.

Metam sodium commonly contaminates air in areas where it is used. A model developed by the California Department of Health Services estimated that almost 100,000 people in California are exposed to potentially damaging amounts of metam sodium in air.

Millions of fish were killed by a metam sodium spill in California. Low levels of metam sodium cause malformations in fish.

Metam sodium kills beneficial soil fungi and soil bacteria that cycle nitrogen, an important nutrient.

BY CAROLINE COX

Metam sodium (see Figure 1) is a soil fumigant that was developed in the 1950s.[1] It is "active against all living matter in the soil" and therefore acts as a fungicide, herbicide, insecticide, and nematicide simultaneously.[2] It is sold under a variety of brand names, including Vapam, Sectagon, and Sanafoam.[3]

Use

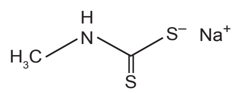
Metam sodium is the most widely used soil fumigant in the U.S.[4] and the third most widely used agricultural pesticide. Based on 2002 estimates, about 55 million pounds are used annually in the U.S. Use is increasing as metam sodium replaces the ozone-depleting fumigant methyl bromide.[5]

About half of the metam sodium used in the U.S. is used in potato production. An additional twenty percent is used in tomato production.[2] Almost 90 percent of U.S. metam sodium use occurs in Idaho, Oregon, Washington, and California.[5]

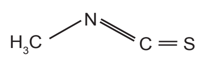
Metam sodium also has a few urban uses, including root control in sewer lines and treatment of utility poles.[4]

Metam sodium is applied at high rates; typical application rates in western states are 150 to 300 pounds per acre.[4]

Figure 1
Metam sodium and MITC



Sodium N-methyldithiocarbamate (metam sodium)



Methyl isothiocyanate (MITC)

How Does Metam Sodium Kill Living Things?

According to the U.S. Environmental Protection Agency (EPA), metam sodium breaks down quickly to a molecule called MITC.[6] (See Figure 1.) MITC is "responsible for the fumigant properties of metam sodium."[6] MITC inactivates certain parts of amino acids, the molecular building blocks from which proteins are made.[2]

Breakdown Products

In addition to MITC, metam sodium breaks down into methyl isocyanate, carbon disulfide, and hydrogen sulfide.[7] Some hazards of these compounds are discussed in "Effects on Pregnancy" and "Effects on Behavior," p. 14.

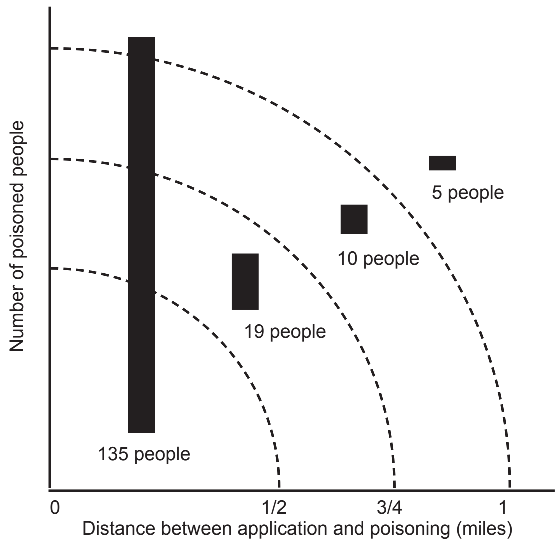
Inert Ingredients

Most commercial metam sodium fumigants contain ingredients other than metam sodium. According to U.S.

■

Caroline Cox is NCAP's staff scientist.

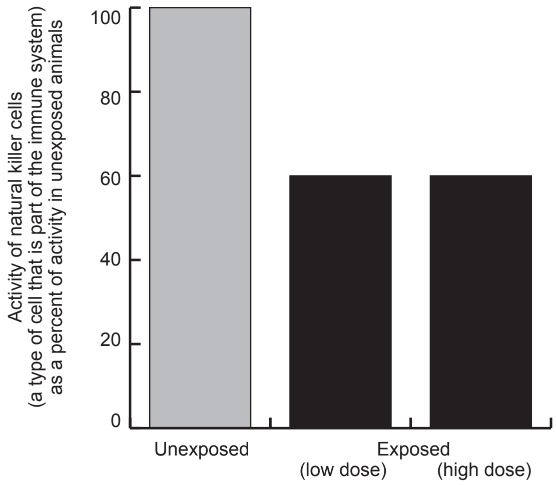
Figure 2
1999 Metam Poisoning Incident in California



O'Malley, M. et al. 2004. Modeling of methyl isothiocyanate air concentrations associated with community illnesses following a metam-sodium sprinkler application. *Am. J. Ind. Med*. 46:1-15.

Metam sodium poisoning incidents have occurred more than a mile from the site where the fumigant was applied.

Figure 3
Effects of Metam Sodium on the Immune System



Padgett, E.L., D.B. Barnes, and S.B. Pruett. 1992. Disparate effects of representative dithiocarbamates on selected immunological parameters in vivo and cell survival in vitro in female B6C3F1 mice. *J. Toxicol. Environ. Health*. 37:559-571.

In laboratory animals, metam sodium exposure reduced activity of immune system cells called natural killer cells.

pesticide law, many of these ingredients are called "inert."[8]

There is not much public information about the identity of these ingredients. In 2000, NCAP asked for information about inert ingredients in metam sodium products through the Freedom of Information Act. Manufacturers of most metam sodium products claimed that this information was confidential.[9]

Most studies conducted to satisfy registration requirements at EPA use metam sodium or MITC alone.[10]

Poisoning Symptoms

Based on calls to U.S. poison control centers, common symptoms of metam sodium poisoning include burns (both superficial and severe), eye irritation, headache, nausea, difficulty breathing, and vomiting. Other symptoms reported to EPA include sore throat, diarrhea, blisters, anxiety, blurry vision, and persistent breathing problems.[11]

EPA has reports of over 700 metam sodium poisoning incidents.[11] Poisoning symptoms have been reported in people as far away as a mile from metam sodium applications, and one incident in 1999 involved over 150 people.[12] (See Figure 2.) Poisoning symptoms occur at concentrations of metam sodium that are too low to have a noticeable odor.[12]

Effects on the Immune System

The immune system is a complex system that protects an individual from bacteria, viruses, and foreign substances.[13] One important part of the immune system is the thymus, an organ that produces some immune system cells.[14] A series of laboratory studies dating back more than a decade has shown that metam sodium and MITC have serious effects on the thymus and other parts of the immune system.

Led by a cellular biologist who has worked both at Mississippi State and Louisiana State Universities, the first studies showed that both oral and skin exposure to metam sodium reduced the size of the thymus and the activity of immune system cells called natural killer cells. The decrease in immune system activity occurred at all dose levels tested. [15,16] (See Figure 3.)

Subsequent experiments showed that MITC reduced thymus size.[17]

Recent research showed that both metam sodium and MITC reduced the production of immune system compounds called cytokines. The researchers calculated that the effects of MITC in this experiment were caused by amounts that would be breathed in by a child near a metam sodium application.[18] The researchers also identified the molecular mechanism through which metam sodium has an impact on cytokines.[19]

In EPA's recent evaluation of metam sodium's human health risks, the only discussion of immune system toxicity is one sentence stating that there is "some evidence that MITC may cause immunotoxicity at high oral and dermal doses."[20]

Effects on Hormones

Hormones are chemical messengers. The hormone system (also called the endocrine system) regulates all biological processes in humans and many other animals.[21]

Metam sodium's effects on hormones

were first described in 1994 when EPA toxicologists working with laboratory animals showed that metam sodium stops the normal "surge" of a hormone that triggers ovulation. MITC had similar effects. Higher doses of metam sodium produce a greater reduction in the surge than lower levels.[22]

Ignoring this research, EPA wrote in its recent evaluation of metam sodium's toxicity that "it is notable that based on the available toxicology studies in metam sodium and MITC, there is no indication of endocrine disruption."[23]

Recent research from Louisiana State University showed an impact of metam sodium exposure on an additional hormone. In these laboratory studies, metam sodium caused an increase in the blood levels of a stress hormone. The increased levels of this hormone then caused atrophy of the thymus.[24]

Carcinogenicity (Ability to Cause Cancer)

In laboratory studies sponsored by metam sodium manufacturers, exposure to this fumigant caused malignant blood vessel tumors.[14,25] (See Figure 4.) Based on these studies, EPA classified metam sodium as a "probable human carcinogen."[25]

EPA's recent assessment of metam sodium risks concluded that most scenarios involving agricultural workers who apply metam sodium exceed the agency's cancer risk guidelines. This is true even with maximum use of protective equipment and engineering controls to minimize exposure.[26]

The California Environmental Protection Agency (CAL/EPA) also classifies metam sodium as a chemical known to cause cancer.[27]

Mutagenicity (Ability to Cause Genetic Damage)

MITC caused abnormal chromosomes in a laboratory study sponsored by a metam sodium manufacturer.[28]

Effects on Pregnancy

Laboratory studies sponsored by metam sodium manufacturers show that exposure to this pesticide can reduce pregnancy success.

One study showed that litters produced by exposed pregnant animals had fewer live offspring than litters produced by unexposed animals. This reduction occurred at all but the lowest dose level used in this experiment.[29]

Another study showed that exposed pregnant animals had more early pregnancy failures than unexposed animals. The increase in pregnancy loss occurred at all but the lowest dose level tested in this experiment.[30] (See Figure 5.)

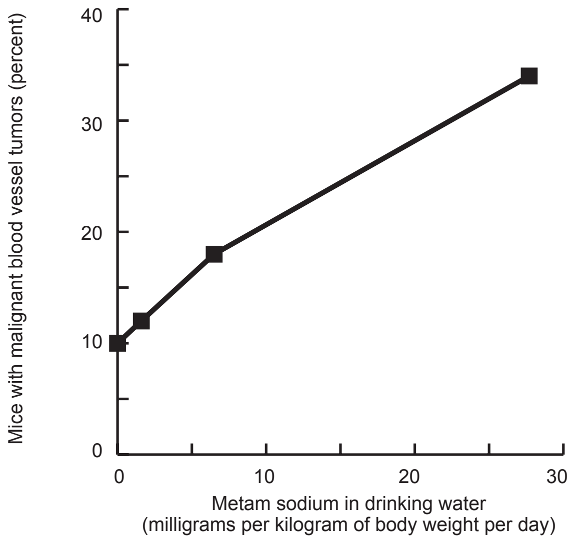
According to EPA, the metam sodium breakdown product carbon disulfide causes fetal loss. In addition, EPA reports that women exposed to methyl isocyanate (another breakdown product of metam sodium) following the notorious Bhopal, India pesticide accident had more spontaneous abortions than normally expected.[31]

CAL/EPA classifies metam sodium as a chemical known to cause reproductive toxicity. [27]

Effects on Behavior

A laboratory study sponsored by a

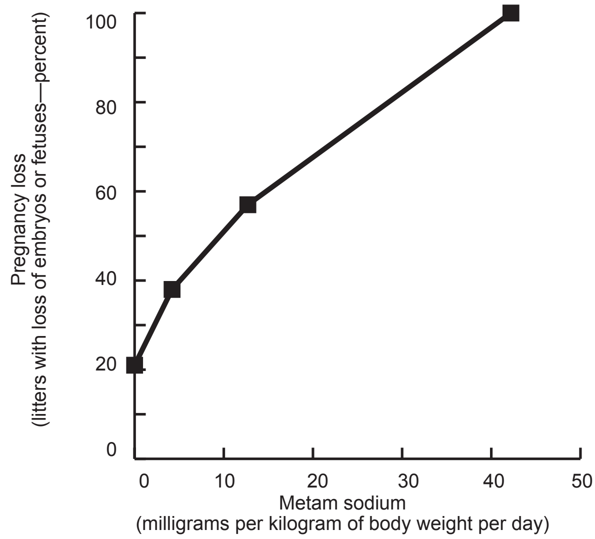
Figure 4
Ability of Metam Sodium to Cause Cancer



U.S. EPA. Office of Prevention, Pesticides and Toxic Substances. 2004. Quantification of carcinogenic potential for MITC with metam sodium cancer slope factor. www.regulations.gov. (Search for EPA-HQ-OPP-2004-0159-0012.)

In laboratory animals, metam sodium exposure caused malignant tumors. Both U.S. EPA and California EPA classify it as a carcinogen.

Figure 5
Pregnancy Loss Caused by Metam Sodium



California EPA. Department of Pesticide Regulation. Medical Toxicology Branch. 2004. Metam sodium (Sodium N-methyldithiocarbamate risk characterization document. http://www.cdpr.ca.gov/docs/risk/rcd.htm. p.64.

Metam sodium caused pregnancy loss in exposed laboratory rabbits. California EPA classifies metam sodium as a reproductive toxicant.

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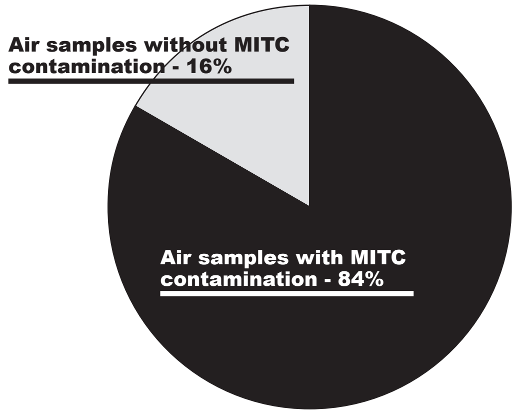
Figure 6
Air Contamination by MITC

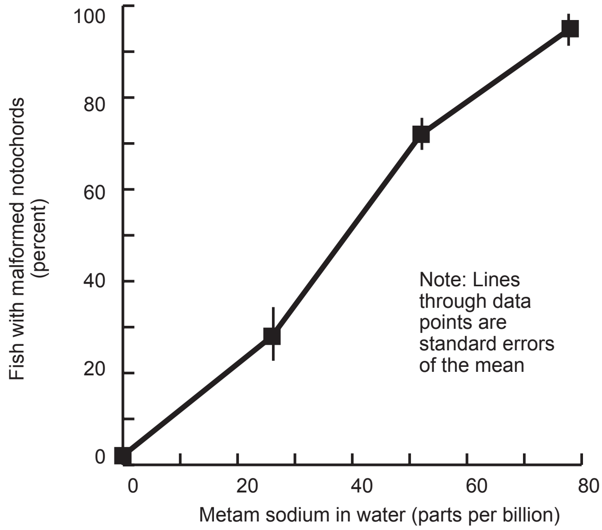


Metam sodium in air samples from rural communities where metam sodium is used

Lee, S. et al. 2002. Community exposures to airborne agricultural pesticides in California: Ranking of inhalation risks. *Environ. Health Perspect*. 110: 1175-1184.

In California, metam sodium frequently contaminates the air in rural communities where it is used.

Figure 7
Ability of Metam Sodium to Cause Malformations in Fish



Haendel, M.A. et al. 2004. Developmental toxicity of the dithiocarbamate pesticide sodium metam in zebrafish. *Toxicol. Sci.* 81:390-400.

Low concentrations of metam sodium caused a nervous system malformation in zebrafish.

metam sodium manufacturer showed that exposure to this fumigant affects behavior. An eclectic collection of behaviors were impacted: breathing, response to an approaching object, leg strength, walking, and motor activity.[32]

The metam sodium breakdown product hydrogen sulfide causes other behavior changes: convulsions, dizziness, weakness, and irritability.[33]

Anemia

Exposure to metam sodium can cause anemia. In laboratory studies sponsored by a metam sodium manufacturer, exposure caused a decrease in the numbers of red blood cells and in the oxygen-carrying molecule found in these cells. In one experiment this occurred at all dose levels tested.[34]

Asthma

According to EPA, a metam sodium spill in California in 1991 resulted in both the development of new asthma cases and the worsening of existing asthma in people who lived or worked near the spill.[35]

In addition, laboratory studies sponsored by a metam sodium manufacturer showed that inhaling metam sodium or MITC damages the respiratory system.[36]

Liver damage

Metam sodium can damage the liver. Pathologists at Vanderbilt University Medical Center showed that a single oral dose of metam sodium caused liver injury and inflammation.[37]

Liver damage also occurred in a test sponsored by metam sodium's manufacturer. In this study, hepatitis occurred at the two highest dose levels tested.[38]

Contamination of Air

MITC is highly volatile[39] (easily turns into a gas) so it often contaminates air.

Recently, the California Department of Health Services assessed MITC air contamination by developing a model based on samples collected in areas where metam sodium has been used. (See Figure 6.) The agency's model estimated that over 50 percent of the people in these areas were exposed to levels of MITC above health guidelines. Almost 100,000 people in California are exposed to potentially damaging amounts of MITC.[40]

Water Contamination

Neither MITC nor metam sodium is included in the U.S. Geological Survey's national water quality monitoring program.[41] This means that there is no systematic information about water contamination. However, EPA notes that metam sodium and MITC are "readily soluble in water and have low absorption into soil, thus these compounds can potentially leach into shallow ground water and leaky aquifers."[42]

Effects on Fish

Recent research shows that metam sodium causes developmental toxicity in fish. (This means that exposed fish do not develop normally.) Scientists at Oregon State University showed that zebrafish embryos exposed to metam sodium developed nervous system malformations when exposed to concentrations as low as 26 parts per billion.[43] (See Figure 7.)

In addition, MITC causes death of fish at concentrations below 100 parts per billion.[44]

A 1991 metam sodium spill in California killed over a million fish in the Sacramento River.[45]

A recent assessment done by fisheries biologists at the Institute of Ocean Sciences in British Columbia (Canada) looked at potential causes for a dramatic decrease in survival of sockeye salmon in the Fraser River. Three pesticides, including metam sodium, were classified as "high risk" in this analysis, along with a variety of other pollutants.[46]

Effects on Other Animals

Metam sodium is toxic to a wide variety of animals. Examples include the following:

- Concentrations of a few parts per million of metam sodium kill oysters and shrimp.[47]
- Concentrations of less than a hundred parts per billion of MITC kill water fleas.[47]
- The 1991 Sacramento River spill reduced the number of salamanders in and around the river by more than 90 percent for at least three years.[48]

Effects on Soils

Recent studies suggest that applications of metam sodium can impact many of the living organisms that are necessary for a healthy soil.

For example, a 2004 study from China Agricultural University looked at free-living, beneficial nematodes in soil. The researchers found that metam sodium fumigation reduced the numbers of free-living nematodes in tomato fields by as much as 80 percent.[49]

Metam sodium can also inhibit mycorrhizal fungi (a kind of beneficial fungi) in soil. Research by the U.S. Dept. of Agriculture showed that fumigation reduced mycorrhizal fungi on sorghum. The reduction was as much as 98 percent in some of these experiments.[50] Impacts on mycorrhizal fungi were also found by scientists from Leiden University (The Netherlands.)[51]

Fumigation with metam sodium also can change the bacterial community in soils, with persistent impacts on bacteria that cycle nitrogen, an important plant nutrient. In a study from Japan, the numbers of these bacteria were reduced by over 99 percent.[52]

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Appendix 3: Agricultural and Veterinary Chemicals Code Instrument No. 4 (MRL Standard) 2012

As amended under subsection 32(1) of the Agricultural and Veterinary Chemicals (Administration) Act 1992

This compilation was prepared on 23 January 2014 taking into account amendments up to Agricultural and Veterinary Chemicals Code Instrument No. 4 (*MRL Standard*) Amendment Instrument 2014 (No. 1)

Prepared by the Australian Pesticides and Veterinary Medicines Authority (APVMA)
Excerpt for Levy vegetables

Compound: Dithiocarbamates (mancozeb, metham, metiram, propineb, thiram, zineb and ziram)

Code		Crop	MRL mg/kg
VS	0621	Asparagus	T1
VP	0061	Beans, except broad bean and soya bean	2
VR	0574	Beetroot	1
VB	0040	Brassica (cole or cabbage) vegetables, Head cabbages, Flowerhead brassica	2
VP	0522	Broad bean (green pods and immature seeds)	2
VA	0035	Bulb vegetables (except garlic, bulb onions)	T10
VR	0577	Carrot	1
VS	0624	Celery	5
VP	0526	Common bean (pods and/or immature seeds)	2
VC	0045	Fruiting vegetables, Cucurbits	2
VO	0050	Fruiting vegetables, other than cucurbits [except roselle]	3
VA	0381	Garlic	4
HH	0092	Herbs [except Parsley]	T5
VL	0053	Leafy vegetables	5
HH	0740	Parsley	5
VR	0588	Parsnip	T1
VP	0063	Peas (pods and succulent, immature seeds)	2
VR	0589	Potato	1
VD	0070	Pulses	0.5
VR	0494	Radish	T1
VS	0627	Rhubarb	2
VO	0446	Roselle [Rosella]	5
VR	0497	Swede	T1
VR	0506	Turnip, Garden	T1

Appendix 4: Soil applied chemical alternatives to Metham Sodium (various sources)

Alternative	Use	Status	Application	Benefits	Disadvantages and/or risks	Which crops does it apply to?	Cost per hectare	References
Chloropicrin	Broad-spectrum antimicrobial, fungicide, herbicide, insecticide & nematicide	In use in Australia and overseas	Used as a replacement for MB, or applied in conjunction with MB, 1,3-D (see beneath) or MITC. Shank-applied as a broadcast treatment, or by shank or drip applications to the planting bed.	Used a pre-plant fumigant against *V.dahliaei* in strawberry production. Reduces or replaces the use of MB.	Less effective against nematodes and weed propagules than MB. Stability in soil is relatively short due to microbial degradation. Applications need to be high when used as a stand-alone product. May stimulate some weed seed germination. Kills beneficial soil organisms – total soil sterilant.	Strawberries Carrots (in conjunction with 1,3D)		Martin (2003) Davison & McKay (2013) Hay et. al. (2013)
1,3-Dichloropropene (1,3-D)	Fumigant and nematicide	In use in Australia and the USA. Banned in the EU in 2011.	It is applied either alone or with mixtures of chloropicrin to improve efficacy against soilborne fungal pathogens (e.g. Telone C35). Broadcast treatment by shank followed by compaction of the shank traces or application of polyethylene tarps. Application of emulsifiable 1,3-D through drip lines.	Nematicide that also has fungicidal properties. Reduces or replaces the use of MB. Cost effective. Telone (1,3-D) and Telone C35 (1,3-D and Chloropicrin) have found to be effective in controlling nematodes in field trials in carrot crops in W.A. (Davison & McKay 2013). Telone is an effective alternative to metham sodium and fenimaphos for nematode control in carrots. Telone C35 has a broader fumigation activity than Telone.	Use was suspended in California in 1990 and reinstated in 1994 due to air quality concerns. Safety and handling concerns. Has been banned by EU Member States in 2011. Enhance biodegradation can be an issue. Applications need to be managed so that enhanced biodegradation doesn't occur. Kills beneficial soil organisms – total soil sterilant.	Tomatoes Strawberries Carrots	Application cost is approximately half the standard MB + Pic broadcast fumigation (Martin 2003). Telone is less than half the cost per hectare of Telone C35. In W.A. field trials Telone was applied at 100kg/ha and Telone C35 at 270kg/ha.	Martin (2003) Dal Santo & Holding (2009) Davison & McKay (2013) Hay et. al. (2013)
Dazomet	Fumigant for germinating seeds of weeds, soil fungi, and nematodes	In use in Australia and overseas including Europe (as regulated)	As for MS, similar product group mainly used as granular product	Alternative to MB but similar to MS controlling Pythium, Phytophthora, Sclerotinia, Sclerotium, Rhizoctonia, Verticillium, Plasmodiophor a Armillaria and Fusarium spp. soil insects and non-cyst forming nematodes	As for MS	All for the treatment of seed beds	Similar to MS	Dazomet label and APVMA review Annex 1 of Directive 91/414/EEC on plant protection products
Ethanedinitrile	Fumigant for germinating seeds of weeds, soil fungi, and nematodes	Australia - trialled in strawberry crops. Approved as a fumigant of timber.	Application through irrigation systems or by injection into the soil.	It is not listed as a greenhouse gas or ozone depleting substance. Lower doses and exposure time than MB, but achieves an equivalent level of pathogen and weed control. Reduced toxicity to human health and the environment (than MB). Excellent penetration in moist soil, high toxicity to insects, nematodes, fungi and weeds. Easy application through irrigation or injected into soil.	Kills beneficial soil organisms – total soil sterilant. Enhanced biodegradation may become a concern. The product is new and information is not available at this stage.	Strawberries		Mattner et. al. (2006) Waterford et. al. (2004)

Alternative	Use	Status	Application	Benefits	Disadvantages and/or risks	Which crops does it apply to?	Cost per hectare	References
Fenamiphos	Insecticide and nematicide.	Under review in Australia. Banned in the USA. Approved in the EU until 2017.	Applied as a pre or post-plant treatment.	Provides effective control of nematodes and sucking insects including aphids and thrips.	Negative environmental impacts – reported bird and fish deaths related to Fenamiphos use in Australia. Also issues relating to contamination of groundwater and waterways due to leaching from sites of application. Banned in the USA – continued use in Australia is uncertain. Potential health risks to consumers. Effectiveness reduced by enhanced biodegradation. Kills beneficial soil organisms.	Vegetable crops Turf		AVPMA (2013)
Fludioxonil	Fungicide. Can act as an insecticide treatment in combination with metalaxyl-M.	In use in Australia and overseas	Seed treatment or post-harvest treatment for fruit.	Broad-spectrum and effective against most seed diseases. Protects against decay, damping-off and blight.	Does not control diseases caused by *Pythium* and *Phytophthora* spp.	Wide variety of vegetable crops (NOT carrots)		Dal Santo & Holding (2009) NuFarm (2012)
Iprodione	Group 2 fungicide, registered for commercial use.	In use in Australia and overseas	Application is via spraying.	Effective control of fungi. Can be used to treat Sclerotinia.		Tree crops and vines. Vegetable crops include celery, lettuce, potatoes and tomatoes. Ornamentals Recreational turf	Rate per hectare: 800ml/100kg seed Concentration: 500g/L	Dal Santo & Holding (2009)
Metalaxyl or Metalaxyl-M	Group D fungicide	In use in Australia and overseas	For carrots – application of dry granules to the soil is recommended at the time of planting or early seedling stage. Rainfall or irrigation is required after application.	Control of damping off (*Pythium* spp. in a number of vegetable crops and *Phytophthora* spp. in peas). Most vegetable seed will come pretreated with a seed protectant such as Metalaxyl.	Resistance issues.	Carrots and other vegetable crops. Fruit and nut trees.	Rate per hectare: 40kg/ha Concentration: 25g/L	Dal Santo & Holding (2009)
Quintozene	Fungicide	In use in Australia and overseas (USA and Canada). Banned in the EU.	A seed dressing, seedling drench, a pre-plant soil-applied fungicide for vegetables, cotton and ornamentals.		APVMA (2010) testing found high levels of dioxins in products containing quintozene. The APVMA report that this could be a risk to health for workers applying the products. The APVMA advise that other alternatives are available.	Vegetables – broccoli, Brussels sprouts, cabbage and cauliflower. Cotton and ornamentals	Rate per hectare: 150g/100L water Concentration: 750g/kg	Dal Santo & Holding (2009) APVMA (2010)

Alternative	Use	Status	Application	Benefits	Disadvantages and/or risks	Which crops does it apply to?	Cost per hectare	References
Thiabendazole	Fungicide	In use in Australia and overseas	It is a systemic benzimidazole fungicide used to control fruit and vegetable diseases such as mold, rot, blight and stain. It is also active against storage diseases and Dutch Elm disease.		Potential to increase soil acidity. It is persistent in the soil.	Sweet potato	Rate per hectare: 1L/22L water Concentration: 500g/L	Del Santo & Holding (2009) Cornell University (2008)
Methyl Iodide (Iodomethane)	Pesticide, fungicide, herbicide, insecticide, nematicide and soil fumigant.	In use in Australia and overseas	Application is the same as for MB+Pic. Can be applied by shank in combination with cholorpicrin. Drip lines have been effective for strawberries.	Closest potential direct replacement for MB. Higher vapour pressure than other potential alternatives, functions effectively as a soil fumigant, has a broad spectrum against soil pests similar to MB and application is the same as MB. Has a longer persistence in the soil than MB. It is not ozone depleting like MB and is a liquid, rather than a gas, at room temperature.	Potential groundwater contamination and phytotoxicity due to long persistence in the soil if plant-back intervals are not followed.	Carrots – reported to be an effective fumigant in a carrot production system. Peaches Strawberries		Martin (2003)
Propargyl Bromide			Applied by shank or drip.	Weed control equal to the standard broadcast of MB in strawberry production trials. Effective control of nematode populations to a depth of 150cm in vineyard trials.	Stability problems in early trials. Soil type has an influence on the stability of propargyl bromide.	Strawberries Vineyards		Martin (2003)
Ozone			Generated using portable ozone generators and applied into tree replant sites by shank or into tarped/untarped, preformed or flat beds through PVC pipes or subsurface drip irrigation lines buried at a depth of 7.5 to 15cm.	Rates as low as 28kg/ha controlled root knot nematode in some carrot and tomato sites. It is an option for organic growers.	Efficacy is dependant on the pest problems present at the site, with nematodes more sensitive than fungal pathogens.	Carrots Tomatoes Strawberries		Martin (2003)

Appendix 5: Biological organisms and materials as disease control products: US (University of Massachusetts Amherst 2014)

Trade Names	Organism	Target Pests	Crops	Comments
ActinoGrow	*Streptomyces lydicus* WYEC 108	*Fusarium, Rhizoctonia, Pythium, Phytophthora, Sclerotinia, Verticillium,* Powdery mildew, Downy mildew, Anthracnose	Beans, peas, corn, potatoes	
Bio-Soil Inoculant	*Bacillus* species		All crops	Soil treatment OMRI (organic certification) listed
Bio-Tam[OG]	*Trichoderma asperellum* &*Trichoderma gamsii*	*Fusarium. Rhizoctonia, Pythium, Phytophthora, Sclerotinia, Sclerotium, Verticillium*	Corn, Cole crops, Fruiting vegetables, cucurbits, leafy vegetables, legumes, root, tuber, and corm vegetables, herbs, onions	Soil treatment OMRI listed
Companion Liquid Biological Fungicide	*Bacillus subtilis*GB03	Anthracnose, *Botrytis*, bacterial diseases, Powdery mildew, *Phytophthora, Pythium, Rhizoctonia*, Leaf spots	All crops	Soil treatment, hydroponics, seed treatment
Cease[OG]	*Bacillus subtilis*QST 713 strain	*Rhizoctonia, Pythium, Phytophthora, Fusarium*	Most crops	Soil drench OMRI listed
Contans WG[OG]	*Coniothyrium minitans* Strain CON/M/91-08	*Sclerotinia sclerotiorum* *Sclerotinia minor*	Most crops	Soil treatment OMRI listed
DiTera DF[OG]	*Myrothecium verrucaria* Strain AARC-0255	Nematodes	Celery, lettuce, spinach, crucifers	OMRI listed
Galltrol A	*Agrobacterium radiobacter* K84	Crown Gall-*Agrobacterium tumefaciens*	Small fruit, nuts, and ornamental nursery stock	

Trade Names	Organism	Target Pests	Crops	Comments
Integral	*Bacillus subtilis* MBI 600	*Rhizoctonia* and *Fusarium* seedling diseases, Fusarium wilt	Legumes, corn, alfalfa and forage	Seed treatment
Kodiak	*Bacillus subtilis*GB03	*Fusarium, Pythium, Rhizoctonia*	Seed and pod vegetables	
Mycostop[OG]	*Streptomyces griseoviridis*Strain K61	*Fusarium, Alternaria, Phomopsis, Botrytis, Pythium, Phytophthora, Rhizoctonia*	Beans, lettuce, carrots, crucifers, onions, spinach, tomato, root crops, herbs	Seed or soil treatment OMRI listed
Plant Shield[OG]	*Trichoderma harzianum* Rifai strain KRL-AG2	*Pythium, Rhizoctonia, Fusarium, Cylindrocladium, Thielaviopsis, Botrytis*, powdery mildew	Eggplant, pepper, tomato, crucifers, lettuce, spinach, herbs	Soil treatment, foliar spray, or greenhouse chemigation. OMRI listed
Prestop WP[OG]	*Gliocladium catenulatum*Strain Ji1446	*Pythium, Phytophthora, Rhizoctonia, Fusarium, Verticillium, Botrytis*	Most crops. See label for crops registered for incorporated or drench treatment only.	OMRI listed
Rhapsody[OG]	*Bacillus subtilis*QST 713	*Alternaria*, bacterial blight (*Xanthomonas*), downy mildew, powdery mildew, *Sclerotinia* spp.,*Botrytis*, rust, *Pytophthora infestans*	Broccoli, carrot, lettuce, onion, pepper, tomato, herbs	OMRI listed Greenhouse Use.
Root Shield[OG]	*Trichoderma harzianum* Rifai Strain KRL-AG2	*Pythium, Rhizoctonia, Fusarium, Cylindrocladium, Thielaviopsis*	Eggplant, pepper, tomato, lettuce, crucifers, cucurbits, herbs, bulb crops	OMRI listed In-furrow treatment
SoilGard 12G[OG]	*Gliocladium virens* Strain GL-21	*Pythium, Rhizoctonia*	All crops	OMRI listed. Soil treatment.
Taegro ECO[OG]	*Bacillus subtilis var. amyloliquefaciens*FZB24	*Rhizoctonia, Fusarium, Sclerotinia, Pythium, Phytophthora,* leaf spots, Powdery mildew	Fruiting vegetables, cucurbits, leafy vegetables	In furrow, transplant drench, basal spray for primarily soilborne diseases. OMRI listed
T-22 Planter Box[OG] **T-22 HC**[OG]	*Trichoderma harzianum* Rifai Strain KRL-AG2	*Pythium, Rhizoctonia, Fusarium, Cylindrocladium, Thielaviopsis*	Beans, carrots, corn, onion, cucurbits, eggplant, pepper, herbs, tomato, crucifers, potato, lettuce, spinach	OMRI listed. Soil treatment

Disease Control Materials (US)

Active Ingredient	Target Pests	Crops	Comments
Hydrogen dioxide (OxiDate[OG])	*Alternaria*, *Phytophthora, Pythium, Rhizoctonia, Fusarium* Wilt, *Sclerotinia*, Anthracnose, bacterial blight, *Botrytis*, powdery mildew, rust	Beans, cucurbits, celery, crucifers, leafy vegetables tomato, pepper, onions, potato, herbs, root crops	OMRI listed. Contact activity only
Saponins from *Quilaja saponaria* (NemaQ)	Nematodes	Brassica crops, Cucurbits, pepper, tomato, Leafy vegetables	OMRI listed
Sesame Oil (Dragonfire-CPP[OG])	Nematodes	All crops	OMRI listed
Sesame Seed Meal (Ontrol)	Nematodes	All crops	Ontrol is not OMRI listed, but many sesame seed formulations are OMRI listed.
Thyme Oil (Proud 3[OG], ProMax[OG])	*Pythium, Phytophthora* species, *Rhizoctonia*, Club root, *Sclerotium* , nematodes	Most crops	OMRI listed

Appendix 6: Factsheet on biofumigation crops and products for vegetables (Vic DPI 2010)

Managing Soilborne Diseases in Vegetables

Vegetable Disease Program IPM

Rotation with green manure and biofumigant crops shows disease control & yield benefits

KEY MESSAGES

- Crop rotation strategies can reduce inoculum of soilborne pathogens by breaking the disease cycle, biofumigation activity (e.g. mustards) and/or improving soil health.
- Biofumigant crops with the highest levels of isothiocyanate (ITC) producing glucosinolate (GSL) compounds were more effective for pathogen control.
- In-field effects of *Brassica* biofumigant crops include excellent weed suppression, a reduction of root rots in green beans and lettuce drop and an increase in the fresh weight of spring onions.
- Biofumigant crops should be pulverised before incorporation into moist soil to ensure biofumigant compounds are released into the soil.
- Some green manure crops showed other soil benefits including increased organic matter, nitrogen and soil biological activity.

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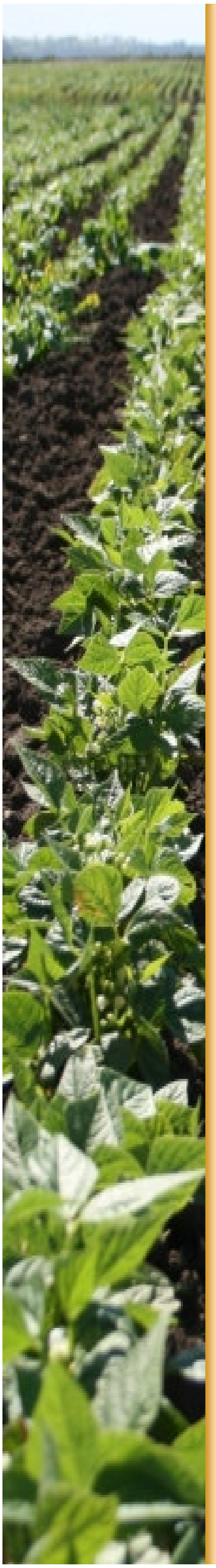

Researchers at Vic DPI, Qld DEEDI and Peracto are finding that green manures and *Brassica* biofumigant crops provide many benefits within vegetable cropping systems. Information from trials including the agronomic characteristics of these crops, their biofumigant potential, effects on key soil health parameters and compatibility with current cropping systems is being used to develop new strategies for managing soil-borne diseases in vegetable production.

Identifying Biofumigant Crops with Anti-fungal Activity

Laboratory and glasshouse studies identified four *Brassica* biofumigant crops, Caliente 199™, Mustclean™, Gladiator™ and Nemfix™, with excellent activity against four major soil-borne pathogens of vegetables. Volatile compounds (ITCs), produced from precursor glucosinolates (GSLs) contained in freeze dried tissue of these biofumigants, were inhibitory and/or biocidal to *Sclerotinia minor*, *Fusarium oxysporum*, *Pythium dissotocum* and *Rhizoctonia solani* (Table 1).

Figure 1. Petri dish assay used to determine biofumigant volatiles effect against soilborne pathogens

Table 1. Effect of biofumigant volatiles on growth of vegetable pathogens in culture, compared with Fumafert™, the standard control, and untreated controls.

Treatment	Relative-GSL content[1]	Rate*	Pathogen: *S. minor*	*P. dissotocum.*	*F. oxysporum*	*R. solani*
Fumafert™	high	0.25	B	B	B	B
		0.50	B	B	B	B
Caliente 119™	high	0.25	I	I	I	B
		0.50	B	B	B	B
Mustclean™	mod	0.25	N	N	N	N
		0.50	N	I	N	N
BQ Mulch™	mod	0.25	I	I	I	N
		0.50	I	I	I	I
Gladiator™	low	0.25	N	-	-	-
		0.50	B	-	-	-
Nemfix™	high	0.25	B	-	-	-
		0.50	B	-	-	-

[1] 2-propenyl-GSL (sinigrin) in shoot tissue, e.g. Caliente 35-70 µMol/g DW. * Rate = grams tissue/ plate
B = biocidal; I = inhibitory; N = no effect; - = not yet tested
Mustclean was more inhibitory at > 0.50g/plate (data not shown)

Effect of Green Manure and Biofumigant Crops on Disease, Yield and Soil)

Field trials in Victoria and Tasmania demonstrated that using Mustclean™ and Caliente 199™ as green manure rotation crops significantly reduced lettuce drop and bean root diseases. For instance, the biofumigation effect of Mustclean™ reduced lettuce drop by 62% and bean root rots by 35%, compared with fallow or grass and cereal rotations. Caliente 199™ had the highest average concentration of shoot GSL (2-propenyl) across all Victorian field sites although the concentration recorded in tissue collected at Lindenow was low due to uneven plant growth (Table 2). At this site legume crops including faba bean and, to a lesser extent, vetch were also a good rotation choice providing similar levels of disease control to biofumigants. These preliminary results indicate potential disease control benefits which warrant further investigation over the long term. At another site, Caliente 199™ increased the fresh weight of spring onions by 16%. In addition, results showed that some of the green manure crops improved soil health by increasing organic matter, nitrogen and beneficial microbial activity.

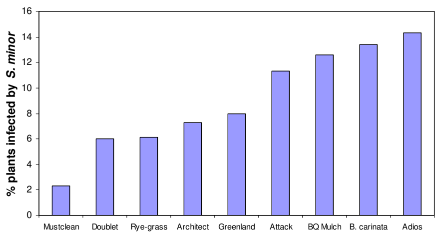

Figure 2. Effect of biofumigation with eight biofumigant plant varieties (rye-grass is the control) on lettuce drop caused by *S. minor* in Tasmania.

Managing Soilborne Diseases in Vegetables

Table 2. Effect of biofumigants and green manures on root rot severity and yield of green beans at Lindenow, Victoria. Means in a column with different letters are significantly different (P≤0.05).

Crop	Biomass (t/ha)	Shoot GSL[1] (µmole/g dry wt)	ITCs soil[2] (mg/kg)	Root rot[3] severity	Yield (t/ha)
Caliente 199™	46.0	24.5 a (48.2)	0.194 a	2.1 c	9.0
Mustclean™	50.7	25.5 a (21.5)	0.713 b	1.9 c	7.2
BQ Mulch™	71.0	31.6 b (29.3)	0.556 b	2.3 bc	8.0
Faba bean	48.3	-	-	1.8 c	8.4
Vetch	32.6	-	-	2.2 bc	8.1
Ryegrass	62.2	-	-	2.9 a	7.8
Triticale	54.1	-	-	2.8 ab	8.0
Fallow	-	-	0.000	2.9 a	6.5

[1] 2-propenyl GSL measured in shoot tissue. Mean for Lindenow and numbers in brackets are means of 3 trials.
[2] The major ITC constituents were allyl-ITCs, 2-phenylethyl and 3-butenyl.
[3] Root rots were caused by *Pythium, Fusarium* and *Rhizoctonia* spp.

Crop Selection and Growth

Choosing the right green manure or biofumigant crops to include in a rotation strategy for effective disease management will depend upon many factors such as season, cropping system, soil type and condition and known pest and disease pressures.
Key points to consider are:

- For maximum biomass production, break crops may need fertiliser input if nutrients in soil from previous crop are low.
- For temperate regions, cold tolerant green manure crops should be selected for winter plantings to obtain good biomass production.
- Time to maturity (flowering) varies among cultivars and on the season. For example, in cold weather Mustclean™ matures in 60 days, while Caliente 199™ takes 90-100 days.
- Best biomass production is achieved during warmer weather (see Table 3), but insect pest pressure could be higher on mustards.
- *Brassica* biofumigant crops provide superior weed suppression to grasses and cereals.
- Some *Brassica* biofumigant crops can be highly susceptible to clubroot and should not be used where this disease is a problem.

Table 3. Sowing dates, time to maturity (incorporation) and biomass production of different biofumigant crops trialled in Victoria, Tasmania and Qld.

Cultivar	Site	Common and scientific name[1]	Sown	Incorporated[2]	Biomass t/ha[2]
Mustclean™	Vic	Indian mustard (*B. juncea*)	March	May	87
Mustclean™	Tas	Indian mustard (*B. juncea*)	May	October	30
Mustclean™	Tas	Indian mustard (*B. juncea*)	October	December	77
BQ Mulch™	Vic	Rape/turnip *B. napus/campestris*	March	July	118
BQ Mulch™	Tas	Rape/turnip *B. napus/campestris*	May	October	62
BQ Mulch™	Tas	Rape/turnip *B. napus/campestris*	October	December	65
BQ Mulch™	Qld	Rape/turnip *B. napus/campestris*	February	April	-
BQ Mulch™	Qld	Rape/turnip *B. napus/campestris*	December	January	-
Caliente 199™	Vic	Indian mustard (*B. juncea*)	March	July	95
Architekt™	Tas	White mustard (*Sinapsis alba*)	October	December	50
Adios™	Tas	Oilseed radish (*Raphanus sativus*)	May	October	83
Adios™	Tas	Oilseed radish (*Raphanus sativus*)	October	December	102

[1] Architekt™ and Abraham™ were highly susceptible to frost damage. Other biofumigant varieties evaluated in Tasmania were white mustard (Abraham™ and Attack™), forage rape (Greenland™), oilseed radish (Arena™ and Doublet™) and Ethiopian mustard (*B. carinata*).
[2] Mustards incorporated at flowering. Variation in biomass levels is due to sowing time and soil types.
- Not assessed

Cultivation and Incorporation

The ideal time to incorporate *Brassica* biofumigant crops is at flowering, before any seed is formed. This is the stage when glucosinolate concentration is at its peak, and also prevents these plants from becoming weeds.

For the best effect, the crop should be completely macerated before incorporation into moist soil to release the isothiocyanate (ITC) compounds. These compounds are highly volatile, so the soil surface should be sealed by rolling or irrigation after incorporation to minimise their escape from the soil.

Contact:
Caroline Donald (VIC DPI, 03 9210 9299)
Oscar Villalta (VIC DPI, 03 9210 9269)
Hoong Pung (Peracto P/L, 03 6423 2044)

Practical methods to optimise the disease control effect of *Brassica* biofumigants include:

- Pulverising plant tissue using a flail mower with hammer blades before incorporation into moist soils.
- Sealing the soil surface with a roller attached to the back of the rotary hoe and/or with irrigation.
- Incorporate tissue into moist soil to initiate the breakdown of glucosinolates into ITCs compounds which are biocidal to soilborne pathogens.

Other novel disease management strategies being developed as part of this program

Grafting

In the Northern Territory, field trials using snake beans grafted onto a Fusarium resistant Iron cowpea root stock have reduced the incidence of Fusarium wilt by as much as 98%. The feasibility of adapting this technique to other vegetable crops is being investigated.
Contact Barry Condè (NTDR) 08 8999 2265

Figure 3. Alternating rows of healthy (grafted) and unhealthy, Fusarium wilt affected (non-grafted) snake beans

Fungal Derived Volatiles

Australian native plants have been found to be excellent sources of endophytic fungi that produce volatile antimicrobial metabolites. A total of 18 endophytes (from one genus) demonstrated strong antimicrobial activity against key soil-borne pathogens of vegetable crops *in vitro.* Mycofumigation produced results equivalent in pot trials to the commercially available fumigant Basamid®, reducing inoculum of *R. solani* by >99%.

Table 4. A comparison of the effects of mycofumigation with Isolate 1.1 and the commercial fumigant Basamid® on populations# of *Pythium* spp. and *Rhizoctonia solani* (AG 2.1) in soil.

Treatment	*Pythium* spp. DNA (pg / g soil)	*Rhizoctonia solani* (AG 2.1) DNA (pg / g soil)
Untreated	179	10,581
Isolate 1.1	65	4
Basamid®	4	0
P Value	0.004	<0.001
LSD (5%)	131.5	5571.3

 # - pathogen populations in soil quantified by amount of DNA present

Disruption of Fungal Resting Structures

Melanised fungal structures called sclerotia enable many fungal pathogens to survive for long periods in soil. Fundamental research has identified the pathway by which *Sclerotinia* produces melanin. Chemical disruption of this pathway resulting in inhibition of sclerotial development and/or melanisation has been demonstrated. Work is continuing to identify genes involved in sclerotial formation. These may provide targets for sustainable control of *Sclerotinia* and other soil-borne plant pathogens.
Contact Kim Plummer (La Trobe University, 03 9479 2223)

Plant Derived Compounds

Inhibitory and biocidal activity and soil-borne disease control potential of thyme, clove bud and origanum has been demonstrated using *in vitro* and pot bioassays. Further work is required to optimise in-field application rates and methods.
Contact Caroline Donald (VIC DPI, 03 9210 9299)

Appendix 7: Integrated Pest Management for Meloidogyne species (Root-knot nematode) (Hay et. al. 2013)

Non-chemical control methods	
Exclusion	▪ Limit the spread of root knot nematodes across paddocks and farms through farm hygiene and wash-down of equipment. ▪ Use certified planting material.
Short periods of bare fallow	▪ Removes host plants (including weeds) from the soil, so that juvenilles have limited food reserves and die of starvation. ▪ Most effective when the soil is warm and moist (this is when juvenilles are most active and will expend their food reserves searching for host plants). ▪ Not as effective in cool, dry soil as juvenilles are relatively inactive and can survive longer periods without a food source. **Disadvantages** ▪ Negative impact on soil health – carbon levels decline. ▪ Exposes soil to wind and water erosion.
Cultivation	▪ Destroys root systems and food sources for nematodes. ▪ Reduces nematode populations through physical effects and exposure to drying. **Disadvantages** ▪ Potential negative effects on soil structure e.g. crusting of seedbeds and soil erosion. ▪ Reduces organic matter and soil biology. ▪ Nematodes can occur deeper in the soil than the cultivation zone.
Resistant break crops	▪ Resistant crop does not provide a food source for nematodes, causing them to die of starvation. ▪ Does not have negative soil impacts ▪ Important considerations in selecting a crop: 1. Climatic conditions 2. Level of resistance to *Meloidogyne* species 3. Capacity of crop to establish, produce biomass and smother weeds 4. Capacity of the crop to harbour other pathogens relevant to the next crop **Disadvantage** ▪ Resistant crops may not be effective where weeds that are alternative hosts of nematodes are abundant. The rotation crop will be ineffective unless implemented alongside an integrated weed management approach. ▪ May not be effective in cool climates. The rotation crop would be grown in winter (e.g. after autumn harvest and before spring sowing), during which time nematode activity is slowed.

Non-chemical control methods	
Trap cropping	▪ For cool climates where resistant crops are not as effective. Involves planting a rotation crop in autumn, which is ***susceptible*** to root knot nematode e.g. acting as a 'trap'. ▪ Juveniles invade and form a feeding site on the roots while the soil is still warm in autumn. They develop slowly as the soil temperature cools in autumn/winter and then the crop is cultivated in late winter/early spring before eggs are laid. Timing of crop cultivation is critical – must occur before egg-laying stage. ▪ A herbicide can be applied if conditions are too wet for cultivation. ▪ Weeds can also act as a trap crop – therefore weed control is not necessary. **Disadvantage** ▪ Requires knowledge of the type of *Meloidogyne* species and their life-cycle so that planting and cultivation occurs at the right time.
Adjusting planting date and harvest date	▪ In cool and temperate climates, planting vegetable crops in late winter/early spring when soil temperatures are cool and nematodes are not very active, can allow crops to establish and delay nematode invasion. ▪ In subtropical regions, planting can be delayed until late autumn, ensuring crops develop over the coolest months. ▪ Harvest date can be brought forward to reduce damage by root knot nematodes. ▪ Short season vegetable varieties can be used to reduced damage. ▪ Storage temperatures are also important and should be lower than the threshold for root knot nematode activity to prevent further damage to tubers after harvest.
Soil solarisation	▪ Laying a transparent polyethylene sheeting over moist soil for 6 – 12 weeks. ▪ Heats soils to temperatures (>40^{o}C) that are lethal to nematodes and other soil-borne pathogens. ▪ High soil moisture content must be maintained so that heat is transferred to deeper soil horizons – therefore most effective in soils with a high water holding capacity. ▪ At the end of solarisation, the plastic can be painted white and used a mulch. ▪ Most effective when combined with other control practices e.g. application of a nematicide. **Disadvantage** ▪ Not as effective in sandy soils, which have a poor water holding capacity. ▪ If solarisation period is too short, nematodes may quickly migrate back into the solarized zone. ▪ Solarization can kill beneficial biological control agents, negating the effect of solarisation to control nematode populations.
Biofumigation with *Brassica* species	▪ Release of volatile breakdown products e.g. ITCs (also the active ingredient in MS) produced when *Brassica* tissues decompose in the soil. ▪ Dried meal prepared from biofumigant plants can be incorporated into the soil instead of cropping a *Brassica* crop. **Disadvantage** ▪ Not as effective as chemical fumigation. ▪ Results can be variable. ▪ Most *Brassica* species are good hosts of nematodes, therefore should be grown in cooler months when nematode development is slowed. *Brassica* must be incorporated before the first generation of eggs is produced. ▪ There is plant-back period, as with chemical fumigants, to ensure phototoxicity does not occur to seedlings. ▪ May be less effective in soils where MS has degraded.

Non-chemical control methods	
Organic amendments	▪ Organic matter includes animal manures, poultry litter, composts, sawdust, composted municipal wastes and cover-crop residues. (http://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/soil/compost-factsheets) ▪ Can be applied as mulch or incorporated into the soil. ▪ High N concentrations can release ammoniacal nitrogen, which kills nematodes. ▪ Can enhance the activity of biological control agents e.g. parasitic fungi and predatory nematodes. **Disadvantage** ▪ More research needed to identify the most effective materials and their application to achieve consistent results. ▪ Limited availability in some growing regions. ▪ High application rates are required (often >50 t/ha). ▪ Transportation costs. ▪ Frequent application to sustain microbial activity, especially in warm, moist soil.
Optimal water and nutrient management	▪ Good water and nutrient management is critical to reducing yield losses in crops infested with root knot nematode and increasing plant tolerance to infection.
Rapid destruction of infested root systems after harvest	▪ Disc the field immediately after harvest. ▪ The nematode population cannot continue to multiply when root system is destroyed. ▪ Many nematodes will be brought to the surface – heat and drying will kill them. ▪ Results in immediate reduction in nematode population.
Plant resistance	▪ Nematodes are unable to develop and reproduce normally in resistant plant varieties. ▪ Likely to become an increasingly important management mechanism. **Disadvantage** ▪ Nematode-resistant varieties are not widely available in the vegetable industry. ▪ Repeated plantings can lead to resistance-breaking strains of nematode. Should be rotated with susceptible crop varieties.
Biological control	▪ Play an important role in an integrated management system alongside other techniques. ▪ Present in all soils and can be enhanced through improving soil organic matter. **Disadvantage** ▪ Currently no commercially available biological products to control root knot nematode.

Appendix 8: Management options for soilborne diseases

This information is an excerpt from VG13045 Review of Soilborne Disease Management…

Pathogen	Biological/Physical	Cultural	Chemical
***Sclerotinia* spp.** *S. sclerotiorum* *S. minor* **Key pathogens** because – Long survival Inoculum reduction difficult Wide host range Limited economic rotations Airborne and soilborne inoculum	*Trichoderma* as a biological control agent (BCA) – impractical, inconsistent; delivery system and survival problems	Risk assessment - Avoid blocks with disease history	Mainly synthetic chemicals; variable success.
		Rotations – limited. Long (4-10 years); only monocots. Biofumigant crop preceding - sequences cannot include solonaceous, lettuce, legumes. Rogue early-infected plants	Filan, Switch, Shirlan (some hosts). *Placement*: drench; transplanting spray; row closure sprays. *Timing*: for *S.minor* (thinning) and for S.s (flowering) -lettuce
	Soil structure mgt – Controlled traffic farming (CTF) – not developed for vegetables	Hygiene and Weed control - biofumigation (and synthetic herbicides)	Some fungicide resistance and cross-resistance. Regional monitoring for (benzimidazole and dicarboximides protection
		"Clean" seed and transplants	
	Hypovirulent strains - insufficiently tested for *S. minor*	Cultivars – few resistant *. Crop specific: cos v fancy lettuce; influences – eg. flowering duration, canopy architecture	Fumigation with metham Biofumigation (and cultural)
	Induced host resistance – potential as a chemical / biological response	Organic matter boosts - mulches, compost - unreliable	Calcium foliar sprays; micro-gypsum – under-developed knowledge

Pathogen	Biological/Physical	Cultural	Chemical
	Plant-derived anti-microbials (Voom) –limited testing	Sanitation - minimise soil, water, equipment movement from infested fields	Avoid excess nitrogen
		Monitor weather – esp. rain; predictive value limited (for ascospore release)	
		Microclimate manipulation - *Irrigation* – drip best; minimise foliage wet periods *Humidity* - row direction and plant spacing; canopy type	
		Move to soilless culture – crop dependent	
Pathogen – *Sclerotium* sp.		Inoculum density-disease severity relationship – garlic, onions	Volatile natural stimulants – DADS for *S. cepivorum*
Nematodes Root knot *(Meloidogyne fallax)* Lesion (*Pratylenchus* sp.) **Key pathogens** because – Destructive alone and in complex – eg. with Vert, Fusarium, viruses Soil movement; spread Wide host range In cultivated soils, esp. sandy	Genetic engineering – resistant cultivars for range of Australian soil types, inoculum densities	Pre-plant soil populations and soil type in decision-making on crop and timing	Nematicides and fumigants - pre-and post-plant options
	Suppressive soils; basis of suppressive interactions with fungi	Crop rotation – economics of rotation sequences/break crops grains v. fallow v. biofumigant crops etc.	Treated 'seed'/planting material
	Compaction management – CTF effects on nemas, interactions in complex.	Host resistance*/tolerance in few crops. Cultivar choice limited by markets*	
		Sanitation – limit soil, water movement from infested sites	
	Rapid germplasm screening – potato genetics (horticultural and pathology traits linked)*	Green manure/biofumigant crops for nema reduction – soil type influence	
	Evaluate as complex (with fungi) - green manure, biofumigant crops	"Large seed" disinfestation – hot water, other	

Pathogen	Biological	Cultural	Chemical
***Fusarium* spp.** (many sub-species) **Key pathogens** because – Often in complex with *Rhizoctonia* sp., Pythium spp. and or nematodes Wide host range Some are seedborne Genus present in most cultivated soils – includes, pathogens, saprophytes, host specific strains/races Damping off; vascular wilts (*F. oxysporum*) and crown and root rot (*F. solani*) diseases, and mycotoxin potential in feedstock	Consider as a disease complex in management decisions	Avoidance - soil and "seed" tests; unreliable inoculum density-disease relationship	Fumigation – Telone, metham for protected and high value crops – eg. asparagus
	Limited BCA potential – *Trichoderma*, compost teas not reliable	Grafting (beans, tomatoes) – technically useful; economics unclear for others, eg. melons	Fungicides – 'seed' trts or post -harvest dips. Systemics in-field. Contact fungicides little value for vascular wilts
	In soilless media *Streptomyces, Ps. fluorescens, Serratia* sp - potential	Cultivar choice – Breeding is long-term solution* Some resistant/tolerant hosts amongst tomatoes, peas, garlic	Water source – monitor presence, treatments (esp. for greenhouse crops)
	Hypovirulent races within *F. oxysporum*	Crop rotations long – 3-6 years, but not reliable for host specific wilts	Nitrogen choices - use nitrate nitrogen. High /low N affect different Fusaria
	Total system approach to limit predisposition-stress of other pathogens, poor nutrition etc.	Hygiene, sanitation, roguing Residue management - note feed corn - toxicity potential	pH change for some strains (6.5- 7)
		Avoid wounds; stress minimisation	Some plant volatiles -potential Delivery systems unclear
		Change planting time to avoid interaction or stress periods	Inducing host resistance - systemic acquired resistance – needs development

Pathogen	Biological/Physical	Cultural	Chemical
Damping off, root rots, sudden collapse, fruit rots – in soil and hydroponics		Rotations – few effective in field soils, but greenhouse more important	
		Hygiene – esp important in greenhouse; hydro solutions	
		Hardwood components in composts	
		Roguing	

Pathogen	Biological /Analytical	Cultural	Chemical
Rhizoctonia sp. **Key pathogen** because – Destructive alone and in complex (with *Fusarium* spp. and *Pythium* spp.) Wide host range Some specific AGs x host AGs x disease –eg. black scurf, stem canker "Seed" borne potential Soil movement spread Causes damping off, root rand fruit rots	DNA detection assays eg. potatoes– understanding inoculum level thresholds	Clean seed, planting material * – nursery, certification practices Know seed sources and quality	Fungicides - Seed treatments effective but not for all disease stages
	Predictive value - from AG identification and soil types	Soil / site prep – tillage; avoid undecomposed plant residue	Several effective in field fungicides
	Seed risk categories (eg. as for potatoes)	Watch planting depth - avoid soil in crowns; too deep delays emergence; keep bed tops dry	
		Crop rotation – cereals. Know AG potential	
		Good weed control; sanitation	
		Use green manure (if decomposed, pulverised) as compost, humate	
		Genetics – resistance* limited	

US recommended management options

Pathogen	Biological	Cultural	Chemical
Rhizoctonia **sp.** *R. solani*	Inconsistent efficacy in-furrow - *T.harzianum*, *B subtilis;* unreliable - soil/substrate drench *S. lydicus, G. catenulatum;* seed treatment with *B. subtilis*	3+ year rotations Avoid fields with undecomposed crop residue	Several fungicides available. Improved performance in combination
	Organic growers using BCAs* – Serenade, Tenet but not reliable	Cultural awareness – planting depths, soil movement onto and into crown of plants	Telone fumigant not generally used by veg growers
	Some biological + synthetic combinations: eg.+Maxim; T-22 Planter Box (*T. harzianum*)	Some tolerant cultivars eg. Nevada 28-48 loose leaf lettuce resistant to bottom rot	Seed trt – Moncut, Maxim, Moncoat +/- in-furrow treatments
	Soil fingerprints – gene recognition for antibiosis as step towards future biofertilisers (Canadian work)	Promote rapid emergence – warmth, right depth	In-furrow – Amistar, Maxim, Blocker

Pathogen	Biological	Cultural	Chemical
Nematodes Root knot Lesion Stem and bulb *Globodera* spp.	Resistance (Mi gene) breaking nematode populations increasing– eg. root knot (*M. incognita)* USA	Use clean bulbs, sets, seed – high altitude sources (garlic, potatoes) to minimise nematodes and viruses	Fumigants and nematicides – not routinely used in many crops
	Alginate product (on carrots)	Start with tip cultures and limit generational propagation	Green manure crops for lesion – sudangrass, mustard
		Tolerant / resistant cultivars; No resistance for *M. hapla*	
		Weed control	
		Non-host rotations – esp grains for root knot	

Sources: Scott *et al*, 2012; Cornell University, 2012; Cornell University Production Guides, 2012; Cornell Crop Management website; Edwards *et al*, 2011; Lazarovits. G. 2011; Lamers, 2010; UC-IPM website; Hao *et al*, 2009; Davis *et al*, 2007; Koike *et al* 2006, Koike *et al*, 2003

* Registered BCAs approved for use in organic production of many vegetable and cucurbit crops in various US states. Contrans^{TM} has demonstrated efficacy in NY in organic cucurbit production, but has not provided adequate control of *Sclerotinia* spp. on lettuce or beans in Australian trials.

Pathogen	Biological/Physical	Cultural	Chemical
Fusarium oxysporum and ***F. solani***	Move to soilless culture	4-5+ year rotations unless host specific strains	Fungicides – seed treatments, tuber dusts, protectants
	Mycofumigation trials – endophytic fungi on grain applied to soil	Avoidance – best solution if economic Rotations – fallow v. rotations? -good survival as saprophyte	"*Stamina*" – "seed" treatment for *Fusarium* and *Rhizoctonia* spp.
	Anaerobic disinfestation – under different soil types?	Dedicated machinery; minimise soil, water movement; Controlled traffic project – spread (tomatoes)	
	BION – trialled to increase SAR (only assessed in cotton)	Minimised movement of soil, water and infested plant material	
		Minimise other stress on plants – eg. nematodes; wounds	
		Resistant cultivars – host specific eg. melon, cucumbers, beans, garlic, onions, tomatoes	
		Solarisation on small scale sites	

Pathogen	Biological	Cultural	Chemical
Water moulds	Furrow applications *T.harzianum*, *B subtilis;* soil/substrate drench *S. lydicus*– inconsistent results	Plant in well-drained soil; avoid saturated conditions	Fungicides – seed treatments and post-planting
		Avoid overhead irrigation; progress towards drip irrigation	Good systemic fungicides Monitoring resistance development – Methenoxam, Reason, Ranman
		Breeding for resistance	Oxygenation of hydroponic solutions

Pathogen	Biological	Cultural	Chemical
***Verticillium* sp.**	Nothing reliable	Avoidance; strain and inoculum density important	None
	Inoculum density testing pre-plant guides site selection	Crop rotation with non-hosts	Fumigant replacements – not very effective
		Good weed control – they may be alternative hosts	High nitrogen amendments can decrease wilt
		Resistant cultivars. Plant susceptible ones only in winter. Spinach. Lettuce priorities	
		Pathogen-free planting material eg. tubers	
		Dedicated machinery – minimise soil, water movement	

Pathogen	Biological/Physical	Cultural	Chemical
***Sclerotinia* spp.**	Contrans™ – registered* for incorporation (to infest ground post-harvest) post-harvest and/or to new crop immediately after planting	Avoid blocks with history of disease Avoid high rainfall areas and marginal soils; "still" sites	Fungicides Timing important (eg. lettuce, rosette sprays or thinning
	Trichoderma – seed treatment (soybeans). Foliar spray – limited uptake	Mulch layer barrier to ascospores – practical for some crops	Fungicides. Spray efficiency – complete coverage of blossoms, crop, debris
	Solarisation – inconsistent; but combined with biofumigant crop more potential	Drainage attention. Progress towards drip irrigation	Fumigation –for some higher value crops
	Pre-plant soil testing for inoculum density relevant pathogens	Good sanitation – equipment, soil, water movement	Post-harvest spray to reduce inoculum (sclerotia) - unreliable
		Good weed control Rogue early infected plants	Avoid over-fertilisation, esp. High nitrogen
		Microclimate manipulation - Plant spacing, density; trim foliage; row direction	
		Crop rotation – monocots only; biofumigant crop benefit	
		Deep burial of sclerotia – unreliable; economics unclear	
		Resistant cultivars – few* eg. Black-seeded Simpson heirloom lettuce	

Appendix 9: Alternatives to MS: Factsheet for vegetable growers

Metham Sodium is an organosulphur compound (sodium salt of methyl dithiocarbamate), which is used as a soil fumigant, pesticide, herbicide, and fungicide.

Alternatives to Metham Sodium

Factsheet for vegetable growers 2014

What is Metham Sodium (MS) used for?

Metham Sodium is used particularly in Western Australian export carrot production areas, in greenhouses and other intensive crops such as field-grown broccoli, capsicums and lettuce. The continued reliance on chemical soil fumigants such as MS can largely be attributed to consumer demand for low cost, good quality, nice-looking vegetables. This drives the need for intensification and specialisation in the vegetable industry to maintain economical viability. Unfortunately, this has, in many cases, changed soil conditions and reduced inherent disease suppressive soil properties, thus reinforcing a reliance on fumigation to deal with soilborne diseases, pests and weeds. The environmental and human toxicity of MS are other good reasons to look for effective, commercially viable alternatives.

Bio fumigant crops can help

Integrated approach needed

Replacing a broad-spectrum fumigant with integrated methods requires growers and advisors to understand more about all the pests and diseases that may affect their crops. There are no simple 'drop in' replacements to MS.

Why we need an alternative

1. **Environmental impacts.** MS has a high mobility in the soil and may move through the root zone faster than it is able to convert to the active MITC. This may contribute to an increased risk of leaching to groundwater and/or runoff to nearby waterways causing toxicity to fish and other water life.

MS results in long-term changes in the composition and activity of soil organisms and has the potential to alter important functions like nutrient cycling and pollutant degradation.

2. **Human health impacts.** In the US, MS is listed as a carcinogen and toxicant. Respiratory, eye and throat irritation, diarrhea and rash are some symptoms of exposure to MS. Poisonings have been reported at some distance from the application site. Health effects including liver damage, lung damage, anemia and reduced immunity have been observed in laboratory animal tests.

3. **Diminishing chemical options.** The increasing cost of agricultural chemicals, more regulation around their use, review and deregistration, means options to growers are becoming more limited. It may not be wise to rely on one specific chemical treatment alone for pest and disease control.

4. **Consumer demand and trade restrictions.** Consumers are increasingly driving a shift away from chemical use. Tightening international regulations around the use and application of MS may also restrict future trade and exports.

Biofumigant crops may be the most promising replacement for MS

Biofumigation is the suppression of soilborne pests and diseases by growing plants that contain inhibitory chemicals. The plants can be harvested as rotation crops or ploughed back in as green manure. Some can be used for grazing and to generate biogas. Plants from the mustard family (e.g. mustards, oil seed radish) or sorghum and rocket species have shown potential. Mustards produce chemicals called **glucosinates** in the plant tissue, which are released when cut or chopped. Enzymes break these down further into **isothiocyanates** that act like fumigants – *these are the same chemicals that are released from MS.*

Biofumigant crops also:
- ✓ **Improve soil structure**
- ✓ **Add organic carbon to soil**
- ✓ **Reduce weeds & soilborne pathogens**
- ✓ **Do not persist for long in soil**

Improve soil health by using an integrated approach

5. Enhanced biodegradation

Biodegradation is the process by which organic substances are broken down by living organisms.

Repeated application of MS can lead to **enhanced biodegradation** of the active methyl isothiocyanate (MITC), substantially reducing the efficacy of MS for control of soilborne pests and diseases. This occurs when there is an increase in soil microorganisms that are capable of rapidly degrading MITC.

Enhanced biodegradation can be prevented by using an **integrated approach** to pest and disease management and by not relying on a single chemical treatment.

Large amounts of plastics and waste make solarisation unsuitable for large-scale vegetable production in Australia

Are there suitable chemical alternatives to MS?

Chemical alternatives to MS are limited. Some new generation nematicides are under development and new fungicides have been registered overseas.

Few alternative broad-spectrum fumigants are registered for use in Australia and they are not considered viable substitutes due to their toxicity.

Reviews of chemical soil fumigants in the US and Europe have led to a tightening of regulations there and the development of other resources to improve the safe use of MS.

The general use of MS in Europe is to be phased out by December 2014. These moves make the future use of such chemicals in Australia uncertain.

Issues of enhanced biodegradation (see p2) with repeated chemical use are a concern.

Repeated soil fumigation depletes the soil of beneficial organisms, many of which act as natural control agents against pests and diseases. The depletion of these beneficials can lead to a 'vicious cycle' of repeated chemical use to control more pests and diseases.

Biopesticides could replace MS but none are currently available in Australia.

Solarisation and soil steaming are not considered good alternatives to MS due to their high costs and lack of environmental benefits.

Integrated Crop Protection ICP: the way forward

ICP moves away from sole reliance on fumigants and offers an alternative to the management of pests and soilborne diseases.

It does require practice change and trying multiple approaches. In doing so, you may avoid pesticide resistance or enhanced biodegradation of soil-applied plant protection products.

An integrated approach relies on monitoring for early detection of pests and diseases. It is based on the use of cultural methods and selective products that protect crops while minimizing negative effects on water, air and soil, and on pollinators and beneficial insects.

Biopesticides, biological control, biofumigation and site-specific nutrition management generally all fit well into integrated crop protection.

Remember that any single one of the ICP alternatives, by itself, will lack the cost effectiveness, broad efficacy, and reliability of chemical fumigants. But it is possible to combine a range of integrated approaches to achieve a viable production system.

A range of ICP approaches is recommended:

✓ Biofumigation (see side-bar on p2)

✓ Proven amendments or 'soil/plant health enhancers'

✓ Biocides/biological control (as they come online)

You should also consider the costs and benefits (see more on p4) for your individual situation – and, remember that a replacement for MS may, in many cases, require a change in attitude by all those involved in its use or application.

Integrated Crop Protection cont ...

✓ can reduce costs of unnecessary chemical applications (by being more targeted)

✓ takes a proactive risk management approach (not a blanket approach)

✓ is more long-term and economically and environmentally sustainable

✓ may withstand external changes like increasing chemical regulation

✓ allows marketing of food produced in an environmentally responsible manner

There are some challenges for ICP to replace MS, including the availability of suitable land for crop rotation, potentially the higher labour needs of implementing monitoring and multiple management approaches, and/or costs associated with different products required in an ICP system. There may still be a need for weed control as MS is active against weeds.

Improved marketable yields and longer term soil improvement should, however, provide adequate benefits through reduced fertiliser and irrigation costs, and a reduction over time in pesticide use, especially if new varieties that are disease resistant and efficient in using resources are introduced.

Please refer to the Final HAL Report VG13045 for detailed information on MS alternatives. Available from InfoVeg: http://ausveg.com.au/infoveg/index.htm

HAL Horticulture Australia

RMCG Environment | Water | Agriculture Policy | Economics | Communities

Key points

✓ Sole reliance on fumigants like MS has, in many cases, changed soil conditions and reduced inherent disease suppressive soil properties, reinforcing continued reliance on fumigation to deal with soilborne diseases, pests and weeds

✓ The environmental and human health impacts of MS are other good reasons to look for effective, commercially viable alternatives

✓ There is no direct 'drop-in' product to replace MS

✓ Alternatives to MS (e.g. biofumigation) will work most effectively as part of a broader, integrated management approach like ICP

✓ Changing established systems involves trial and error, uncertainty and risks, while new practices are adapted to existing production systems

✓ New ICP strategies must be developed within a local context that considers the following:

- local soil types and production systems
- disease pressures
- environmental conditions

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Appendix 10: Alternatives to MS: Powerpoint presentation

Alternatives to Metham Sodium

Horticulture Australia

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Environment | Water | Agriculture
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What is Metham Sodium (MS)?

- An organosulphur compound
- Sodium salt of methyl dithiocarbamate
- Used as a soil fumigant
  - Insecticide
  - Herbicide
  - Fungicide
- MS is not suitable for integrated crop protection approaches

MS is used to control:

- Nematodes
- Soil inhabiting insects
- Germinating seeds of weeds
- Soil borne fungi

MS usually is a remedy for severely diseased sites

Consumers' preference for perfect looking vegetables is one driver for continued MS use

Cost / Price pressures are another reason given to explain MS use

Main MS use in vegetables

- Carrot production (mainly WA, also Qld)
- Other intensive crops e.g.
  - grown broccoli
  - Capsicums
  - Lettuce
- Greenhouse crops

Why do we need alternatives?

- Human health impacts

- Exposure to MS can cause symptoms:
  - Respiratory problems
  - Eye and throat irritations
  - Diarrhoea
  - Rash
- Lab animal tests indicate:
  - Liver damage
  - Lung damage
  - Anemia
  - Reduced immunity

MS is listed as a carcinogen and a toxicant in the US and EU; it is strictly regulated in the US and discontinued in the EU

Why do we need alternatives?

- Environmental impacts

- High mobility in soil
- Can moves through root zone faster than it can convert to the active MITC
- May leach to waterways
- Affects level and diversity of soil life
- Can affect nutrient cycling and pollutant breakdown

MS can lead to long term changes in soil organisms and thus loss of disease suppressive properties of soils

Why do we need alternatives?

- Diminishing chemical options

- Increasing cost of ag. chemicals
- Increased regulation around chemical use
- Review and deregistration of chemicals
- Options are becoming limited

It is not wise to rely on one specific chemical treatment alone

Why do we need alternatives?

- Consumer demand & trade restrictions

- Consumers want less chemical used in food products
- Tightening international regulations for MS and other chemicals (MRLs)

Will be phased out in Europe by end 2014

Why do we need alternatives?

- Enhanced biodegradation

- Soil organisms rapidly degrade the active MITC when MS is used a lot and over a long time
- Efficacy of MS diminishes
- Leads to a ‘vicious cycle’ of more pests, weeds & diseases and the need for more pesticide use to control them
- Reduction of marketable yield and potential residue issues

This can be prevented by using an integrated approach

Are there suitable chemical alternatives to MS?

- Chemical alternatives are limited
- Few are registered for use in Australia
- Most not considered viable due to toxicity, costs or efficacy
- Reviews and bans overseas and lack of new registrations make future chemical options uncertain
- Repeated use of any chemical fumigant depletes soils of beneficials that can act as natural disease control agents (suppressive soils)
- Markets may not accept broad spectrum pesticide use and or set low MRLs

Integrated Crop Protection (ICP)

the way forward

- A move away from sole reliance on fumigants
- Requires practice change & trying multiple approaches to find out what works
- Requires monitoring for prediction or early detection pests, weeds and diseases
- Uses cultural methods & selective products
- Minimises negative effects on water, air, soil, pollinators, beneficials and people
- Growers find ICP cost efficient once established

Integrated Crop Protection (ICP)
the way forward

- A range of ICP approaches recommended:
  - Biofumigation
  - Proven amendments or 'soil/plant enhancers'
  - Biocides/biological control (when available)
  - Improving overall soil conditions through reducing tillage, cover crops, wider rotation, balanced nutrition

Growers need to monitor the costs and benefits for their production systems, taking a longer term view

Biofumigant Crops

- Suppression of pests & diseases with plants that have inhibitory chemicals
  - Mustards & oil seed radish (not suitable for brassica crop rotations – club root)
  - Sorghum or rocket species
  - Good results when used correctly



Biofumigant Crop benefits:

- Improve soil structure, water holding capacity and nutrient cycling
- Add organic carbon to soil
- Reduce weeds & soilborne pests and diseases

- Do not persist long in soil – no long term negative effects

The most promising replacement for MS

Mustards release the same chemicals as MS without the negative effects

Why Integrated Crop Protection?

1. $$$ reduced costs of chemical applications and financial losses due to poor marketable yields
2. Proactive risk management (people, profit, environment)
3. Withstands external changes like chemical regulation or market pressures
4. Improves soil conditions and resilience
5. Allows marketing with environmental responsibility branding (e.g. EnviroVeg)

Key messages

1. Sole reliance on MS can change soil conditions & reduce natural disease suppression
2. MS has human & environmental health impacts
3. No direct 'drop in' replacement
4. Alternatives will work best as part of an integrated approach
5. Many growers are changing their approach already within the context of their production system

Check the HAL report VG13045 "Identification of Potential Alternatives to Metham Sodium" for details on all alternatives!

Horticulture Australia

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