Review of Soilborne Disease Management in Australian Vegetable Production

Dr Prue McMichael
Scholefield Robinson Horticultural Services Pty Ltd

Project Number: VG11035

VG11035

This report is published by Horticulture Australia Ltd to pass on information concerning horticultural research and development undertaken for the vegetables industry.

The research contained in this report was funded by Horticulture Australia Ltd with the financial support of the vegetables industry.

ISBN 0 7341 3023 6

Published and distributed by:
Horticulture Australia Ltd
Level 7
179 Elizabeth Street
Sydney NSW 2000
Telephone: (02) 8295 2300
Fax: (02) 8295 2399

HAL
Horticulture Australia

Scholefield Robinson
HORTICULTURAL SERVICES

Review
Soilborne Disease Management in Australian Vegetable Production
VG 11035

Prepared for : Horticulture Australia Ltd

By : Prue McMichael

Date : October 2012

Review : Soilborne Disease Management in Australian Vegetable Production : VG 11035

Prepared for: Horticulture Australia Ltd

Prepared by: Prue McMichael

October 2012

Scholefield Robinson Horticultural Services Pty Ltd
ACN 008 199 737
ABN 63 008 199 737

PO Box 650, Fullarton SA 5063
Ph: (08) 8373 2488
Fax: (08) 8373 2442

srhs@srhs.com.au
www.srhs.com.au

Purpose of Report:
The primary outcome of this review is an independent opinion on the key soilborne diseases of vegetables and future investment foci that will advance the capacity of vegetable producers to manage them. The investment opinions are based on an assessment of current knowledge gaps, and the utility of management options that have been identified in volumes of previous R&D.

Acknowledgements:
This project has been funded by HAL using the vegetable industry levy and matched funds from the Australian Government.

The author records here her gratitude for the input received from colleagues, practitioners, corporate researchers and from HAL. Busy people provided opinions, useful insight and assistance. They include international experts: Steve Koike, Mike Davis, Gene Miyao (University of California), Henrik Ypema (BASF); Bryan Delp, Craig Sandlin (Syngenta, USA); Karen Flint-Ward (Washington State, USA); Fred Crowe (retired, Oregon USA), and Hasan Bolkan (retired, Campbells Soup, USA). Local experts included: Kathy Ophel-Keller, John McPhee, Graham Stirling, Caroline Donald, Oscar Villalta; and Ben Callaghan (Horticulture Australia Limited). Cheryl Jenkins and Peter Scholefield (Scholefield Robinson) have provided valuable assistance and support also.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

MEDIA SUMMARY

The strategic management of soilborne pathogens requires knowledge of their biology, their response to the presence or absence of a host, their host range, environmental influences on the host, the pathogen and their interaction. Soil type, health, physical and chemical structure also influence the impact of soilborne pathogens, and of those introduced to soil, eg. on planting material.

Amongst vegetable growers, there is medium-high level awareness of integrated pest management (IPM) and integrated crop management (ICM) and the potential environmental, human and crop benefits potentially derived from these management approaches. The volume of information available on soilborne diseases of vegetables is such however, that few growers can synthesise the components relevant for their specific farming system and current disease threat.

With consideration given to the determinants of key pathogen status, and the regional distribution of soilborne vegetable pathogens in Australia, we have concluded that the top five key pathogens (independently and in complexes) of vegetable crops today, are: *Sclerotinia* spp. (*S. sclerotiorum* and *S. minor*), *Fusarium* spp. (*F. oxysporum* and *F. solani*), Water moulds (primarily *Pythium* spp.), nematodes and *Rhizoctonia* spp.

This review has not re-stated general information or recommendations of past RD&E but rather it has independently assessed the specific *knowledg*e derived that has relevance to soilborne disease management. It also identifies knowledge and 'know how' gaps that are limiting the success growers have in consistent management of these key pathogens.

Risk assessment must underpin planting decisions. Our review suggests that growers at present do not have sufficient knowledge of some risk factors and influences on them; nor of the most timely and economic responses appropriate for their farming system. The responses may include not planting a site, planting a biofumigant crop, or changing the planting date or cultivar. Enabling technologies (i.e. DNA soil assays that can quantify some fungal pathogen and nematode soil populations; profile microbial communities etc.), are being used in other annual crop industries to inform grower decisions before planting.

Vegetable growers in Australia are not lacking in options for the management of soilborne diseases However, in the absence of informed risk assessment, vegetable growers are limited in their capacity to choose and integrate the most appropriate and reliable management options for their farming system. Synthetic chemicals and the use of tolerant/resistant cultivars where available, are therefore relied upon. Few other management options (cultural, chemical, biological, physical, genetic) have been sufficiently tested across farming systems with different soil types, disease pressures, and environmental conditions. In particular the relationship of inoculum density and disease incidence in different soil types and cultivars, is unknown for most of the identified key soilborne pathogens.

Increased efforts and investment in *extension* material and services are strongly recommended. Growers will benefit significantly from practical knowledge packages. They should detail risk factors associated with these pathogens and how they may be assessed for whole farming systems; the economics of management options and inoculum reduction and avoidance measures; and the packages should be focussed on 'adoption-ready' knowledge rather than 'early innovation' information that cannot be implemented with any confidence. Investment in further *development* of risk assessment tools and technology, management options, cultivars, and inoculum reduction practices, is warranted. Some specific *research* on inoculum thresholds, and suppressive soil profiling and characterisation is also needed.

TECHNICAL SUMMARY

Sclerotinia spp., *Fusarium* spp. water moulds, *Rhizoctonia* sp. and nematodes were identified as the top five 'key' soilborne pathogens of vegetables. The impact of these pathogens on multiple crops, their distribution, the requirement for their on-going and regular management, and the inconsistent results of management measures contributed to their 'key' pathogen status. Nematodes were included as their interaction with soilborne fungi and negative impact on productivity continues, despite the availability of efficacious management tools. A similar list of soilborne pathogens of on-going concern was provided by USA pathologists.

There is no shortage of pathology information available to Australian vegetable growers. Despite the volumes of '*information*' from previous RD&E, growers cannot always identify the practical potential or relevance of the information, its readiness for adoption, or its suitability for their farming system or location. The R&D literature does not distinguish clearly 'adoption-ready' outputs from 'early innovation' experimental results. The existing '*knowledge*' gaps limit the capacity of vegetable producers to assess pre-plant, the pathogen-related risk in their soils and environment, for their intended crop.

In general, management and risk reduction practices are categorised as being biological, chemical, cultural, physical or genetic, in nature. Informed management requires proactive and reactive steps informed by risk knowledge and assessment and the purposeful integration of appropriate management practices and technology. The existing knowledge gaps limit capacity to determine and integrate the most economic, reliable and timely responses to risk, eg. changing planting time or crop cultivar, treating soil or seed, or avoiding the site.

The review recommends closing the knowledge gaps, primarily through serious *extension* efforts that organise and deliver essential risk assessment knowledge. Growers require detailed knowledge of practices that are ready for implementation and appropriate for their risk level and farming system. Continued investment in *development* of some management tools and technology, and further *research* in specific areas, is also warranted.

It is our opinion that growers today require co-ordinated, packaged information that increases their capacity to respond to soilborne pathogen risks. The information should be clearly dated and focussed on adoption-ready measures that are linked to the whole farming system. Inoculum density-disease incidence data are necessary for the management of inoculum-dependent problems (eg. those caused by *Sclerotinia* spp., *Sclerotium* spp., nematodes), and technology (DNA based) to identify and quantify pathogens and nematodes in soil before planting is now available and should be utilised to guide site and crop selections. Cultivar decision support should be included, eg. cultivar performance across soil types and under different inoculum pressures. Knowledge on the economics of inoculum reduction strategies (eg. crop rotations) across soil types is also important in risk assessment.

Growers will benefit from ready access to relevant knowledge that is regularly updated. The format of its delivery is important and hard copy risk assessment knowledge packages are recommended, with associated *How to* Guides (eg. for risk assessment, sampling, chemical resistance monitoring, crop monitoring and data management with smart technology etc.). Extension officers are likely to be the best delivery mechanism.

Further development of promising technology (eg. smart technology; pathogen quantification assays) is important to expand its uptake, and relevance (more pathogens and pathogens in complexes) to farming systems. Increased engagement of the nursery and seed sectors in seedborne inoculum data, chemical and cultivar screening across farming systems will be helpful; and a regional approach to chemistry protection and systematic sampling, warrants greater education investment and development. Determination of inoculum thresholds for nematodes has commenced, and requires future research for fungal pathogens. Advancing the research on soil profiling commenced collaboratively in Canada, is recommended as it will in the longer term provide a tool capable of characterising soil communities and predicting suppressive (or stimulatory) potential.

INTRODUCTION

The production of vegetables in soil is an activity of diverse, inherent risk. Soilborne pathogens of vegetables include fungi, bacteria, water moulds, plasmodiophorids, nematodes, some viruses and other organisms. They are amongst the most difficult to reliably control by either synthetic chemicals or soft approaches. Site and crop selection are enhanced by prior knowledge of pathogen presence, and an understanding of the growing environment and agronomic practices that may influence the pathogen population and host response to infection. Some soilborne pathogens may persist long periods in the absence of hosts. Such pathogens warrant on-going grower vigilance to ensure they are not introduced to clean sites, or spread from infested sites. Hygiene, sanitation, vehicle, soil and water movement are therefore important management considerations.

The constraints on pesticide use and community respect for the environment has seen most vegetable growers move towards integrated crop management (ICM). The concept of ICM (and integrated pest management-IPM) is best described as multi-faceted, sustainable risk minimisation steps applied across the crop production system. It incorporates chemical and non-chemical practices to minimise the threat and impact of pathogens, and maximise productivity. Despite awareness of non-chemical and cultural management tools developed as outcomes of extensive research over many decades, reliable 'control' of several soilborne pathogens continues to rely primarily on synthetic chemicals and/or resistant/tolerant host cultivars. Where neither is available, soilborne pathogen management remains difficult and significant losses occur in some seasons in some production locations. Synthetic chemicals, where available, tend to be relied upon at the expense sometimes of environmental and economic sustainability.

Australian researchers have undertaken a large number of research and development (R&D) projects on vegetable pests and diseases. According to the Vegetable Industry Development Program (VIDP), the total Horticulture Australia Limited (HAL)-supported vegetable pest and disease projects outnumber projects in other research focus areas (eg. market and industry development, productivity, people development, etc). During the period 2001-2010, plant health and crop protection research, development and extension (RD&E) was the focus of more than 50 percent of projects.

MATERIALS AND METHODS

In order to focus the review, three questions were addressed: *What Do We Already Know*? *What are the knowledge gaps and how could they be addressed*? and *What is the best way to extend future research that covers these knowledge gaps to the Australian vegetable industry*? The review presents answers to these questions, formulated through reading of previous research literature, experience in vegetable pathology, and through enquiry of researchers locally and internationally.

The components of each question provided a structure for the review and for the report, as follows:

1. What Do We Already Know?

a) What are the five key soilborne pathogens (fungal/bacterial) currently impacting on Australian vegetable production at a national level?

b) What is already known about the management of these pathogens in Australian vegetable production?

c) What work has been done in other crops/industries for these diseases in Australia and what work has been completed on these diseases in vegetable crops overseas that could be of value to the Australian vegetable industry?

d) What key best practice management guides have already been developed for these diseases in Australia and is there evidence that these guides have been well adopted by the Australian industry?

2. What are the knowledge gaps and how could they be addressed?

a) If the Australian vegetable industry were to invest R&D levy funds in the management of soilborne diseases, what are the five priority pathogens that should be addressed?

b) Is there a demonstrated link between quantification of pathogen presence in the soil and disease expression for these key pathogens?

c) What disease management approaches for these pathogens could be investigated for future research that meets the criteria: for efficacy; viable, economic adoption; longer term sustainability; nationwide relevance; farming system compatibility; and with linkage to current research but not commercial developers of similar approaches.

3. What is the best way to extend future research that covers these knowledge gaps to the Australian vegetable industry?

a) What management approaches proposed for future investment require a significant timeframe or level of investment prior to being adoption-ready?

b) How can research and extension materials for such approaches best be delivered to the Australian vegetable industry?

The methodology of review has been appropriate to provide the Australian vegetable industry with independent information to assist decision-making, to close knowledge gaps, and to recommend future RD&E investment foci such that the potential for grower returns in the area of improved soilborne disease management, and therefore profitability, is assured.

RESULTS AND DISCUSSION

This project is a review of recent, relevant RD&E outputs, rather than assessment of the past projects' objectives.

1 SOILBORNE PATHOGENS OF VEGETABLES

Soil ecology is complex and the pathogenic and non-pathogenic microbial populations within cultivated soils include common soil inhabitants, soil invaders that are capable of establishing a population after their introduction, and transient microorganisms. Although a generalisation with exceptions it is reasonable to accept that soilborne pathogens in the top 15-20 cm soil have the greatest impact on most vegetable crops.

Most economically-important soilborne pathogens of vegetables are fungi. However several serious diseases of vegetables are caused by soilborne bacteria eg. *Dickeya* spp., *Ralstonia solanacearum*, *Clavibacter* spp. Few viruses that affect vegetables are soilborne, although those in the Tombusvirus group are. Soilborne viruses like other viruses, can be mechanically transmitted (eg. through grafting, plant or root contact, handling), but some may also be vectored by soilborne fungi or nematodes, and therefore spread by water and soil movement. Lesion and root knot nematodes damage many vegetable crops in Australia, but other nematodes are significant because of associated regulatory and trade restrictions, eg. potato cyst nematode. The interaction of nematodes with other pathogens in disease complexes, and the predisposition of nematode-infested planting material to other pathogens, is frequently reported in vegetable cropping systems. Nematodes may reside and feed inside roots or feed externally, and their impact, as for other pathogens, often reflects soil type, prior crops, host cultivar and its health at planting.

2 KEY SOILBORNE PATHOGENS OF VEGETABLES

2.1 Determinants of "key" soilborne pathogen status

The biology of soilborne vegetable pathogens (life cycle, establishment, spread, reproduction, infection rate etc.), and their pathogenicity, are influenced by the host and alternative hosts (susceptibility, age, root and canopy structure etc.), the growing environment (soil, water, microclimate humidity and temperatures etc.) and wider environmental conditions (eg. weather).

A 'key' pathogen is one that may cause on-going and/or significant negative impact. The negative impact may be local or widespread, occur regularly or irregularly, but it results in economic loss of yield and/or quality - and therefore, profitability. Key pathogen status may be due to:

- Lack of early warning indicators of pathogen presence – eg. detection, prediction, or diagnostic alerts (eg. as might occur with asymptomatic but infected seed lots/ planting material; mutant/resistant strains etc.).
- Lack of disease management options, eg. options are not economically feasible, ineffective and/or impractical; do not manage soilborne and airborne life cycle stages.
- Few inoculum reduction options, eg. as for pathogens/disease complexes with wide host ranges, long-lived survival structures and/or saprophytic capability, lack of effective chemicals etc.
- Environmental influence on pathogen exceeding that of the host –eg. epidemic potential; rapid spread etc.

The 'priority' pathogens across Australian vegetables, as determined by industry groups at national workshops in 2007 (Porter *et al*.) are shown in Table 1.

Table 1 : Priority soilborne pathogens as determined by industry in 2007

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

Other pathogens may cause concern for growers of particular commodities, or have regional impact. Many have 'key' pathogen status as indicated in Table 2.

Table 2 : Key soilborne pathogens of Australian vegetables and 'key' status indicators

	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	✓

[z] Options may include exceptions within each column, but in general no single control option is reliable, practical and economic.

[p] More difficult to predict when part of a complex or having airborne spore stage in life cycle.

* Some host specific; several strains/races yet to arrive in Australia; may produce mycotoxin and become food or stock feed problem.

[v] Another species and defoliating strain are more severe threats. *V. dahliae* resistance in tomatoes may/may not be useful against *V. albo-atrum* which was recently detected in Australian potatoes, but has unknown distribution to-date.

[x] Seedborne potential – seeds, tubers, sets, cloves etc.

2.2 Top five 'key' pathogens of vegetables – Australia

With consideration given to the determinants of key pathogen status (Section 2.1 and Table 2) and the regional distribution of pathogens, this author has concluded the five key pathogens (independently and in complexes) of Australian vegetables today, are:

- ***Sclerotinia* spp.** (*S. sclerotiorum* and *S. minor*)
- ***Fusarium* spp.** (*F. oxysporum* and *F. solani*)
- **Water moulds** (primarily *Pythium* spp.)
- **Nematodes**
- ***Rhizoctonia* spp.**

The above list reflects similar conclusions on pathogen importance in comprehensive reports by Donald *et al* (2010), Donald and Porter, 2010, McDougall (2007), Porter *et al* (2007), and dal Santo and Holding (2009, 2009b-d). International sources working in Mediterranean (California) and sub-tropical (Florida) climates, list the same pathogens amongst those causing on-going concern.

The review of recent literature confirms that the vegetable industry levies have funded with the Commonwealth government (through HAL) a large number of projects on each of the five key soilborne pathogens of Australian vegetables. Primarily, the research has been conducted within an IPM framework and therefore many reports have included or acknowledged evaluation of chemical and non-chemical approaches to the management of these pathogens. Porter *et al* (2007) categorised the foci of such research up to 2007 (Appendix 1).

2.3 Key soilborne pathogens of vegetables – USA

University pathologists, diagnosticians, and/or farm advisors in California, Florida and Washington state, USA provided to this reviewer their current priority soilborne diseases/pathogens of vegetables (Table 3).

Table 3 : Priority soilborne vegetable diseases/pathogens USA[z]

California – coastal (mixed vegetables)	California – central valley (mixed vegetables)	Florida (mixed vegetables and melons)	Idaho/Washington (mainly potatoes)
Verticillium spp. – (esp. spinach, lettuce, tomatoes)	*Fusarium oxysporum** *F. solani*	*Fusarium* spp.	Nematodes
Fusarium oxysporum * *F. solani*	*Verticillium* spp. +/- root knot nematodes (complex)	Sudden wilt complex	Powdery scab
Disease complex: *Pythium*, *Rhizoctonia*, *Fusarium* spp.[x]	Water moulds (esp. *Pythium* spp.)	Nematodes	Black dot
Sclerotinia spp.	*Sclerotinia* spp.	Bacteria – esp. seedborne	Corky ringspot - virus + nematode complex
Sclerotium spp.	*Rhizoctonia* spp. (carrots, potatoes, lettuce)	Water moulds, esp. *Phytophthora* spp.	
Soilborne viruses	Nematodes	*Sclerotium* sp.	
Macrophomina sp.[y]			
Water moulds			

[z] As indicated by R&D pathologists in USA

* Increasing frequency and severity of wilts and crown and root rots. Mycotoxin concern (in corn).

[x] Problem especially with infected transplants.

[y] Since loss of fumigants.

Pathologists conducting research in the same regions of the USA for corporate entities (i.e. seed companies, multi-national crop protection product manufacturers), were asked to identify their key pathogens, and to indicate their current corporate R&D focus relevant to soilborne pathogens of vegetables. Their responses are tabled in Tables 4 and 5.

Table 4 : Current soilborne (and seedborne) pathogen priorities in corporate vegetable research

California – Seed company	Multi-national crop protection product manufacturer	Multi-national crop protection product manufacturer
Geminiviruses	*Monosporascus* sp. (melon vine decline)	*Fusarium* spp. New races
Fusarium spp.	Corky root (lettuce)	*Verticillium* spp.
Verticillium spp.	*Ralstonia* wilt (tomatoes)	Root-knot nematode
	Gummy stem blight and sudden wilt (cucurbits)	*Phytophthora capsici;* and sudden wilt
	Club root (*Brassica* spp.)	*Sclerotinia* spp.
		Sclerotium spp. (veg; turf)

Table 5 : Soilborne pathogen-related research foci

California – Seed company	Multi-national crop protection company	Multi-national crop protection company	Washington State
Breeding for resistance[x] - tomato, capsicum, melons	Fungicide chemistry[x]	Fungicide chemistry – priority for oomycete fungicide/s – seed and post-plant	Potatoes –breeding for resistance to nematodes, virus, powdery scab
Seed quality - disinfestation; seedborne pathogen[x] inoculum reduction	Combination treatments - *Collimonas* root protection + synthetics	Fumigant replacements[x]	Detection and quantification Soil inoculum/disease incidence thresholds[x]
Resistance breaking nematodes – protecting Mi gene in tomatoes	Seed treatments[x]		Potato tuber treatments – chemical + biological combinations
Organic industry alternatives – esp. clean seed, seed treatments			

[x] Specific pathogen target or complex not identified.

3 MANAGEMENT OF KEY PATHOGENS IN AUSTRALIAN VEGETABLES

Agricultural activity influences the host, the pathogen, the growing environment, and their interaction. Pathogen management requires integrated approaches.

Frequently, research has identified a degree of success in risk minimisation or management for a specific host-pathogen relationship, but the transferability of results remains limited or undeclared. The relevance of particular pathogen research to other hosts, soil types, disease pressure or production system situations, is rarely known. Informed management requires purposeful integration of management options, but to evaluate the relevance of results and to adapt them for implementation that has a high potential for success, requires specific knowledge of the risk factors and what influences them in a particular farming system.

3.1 Foundations of soilborne pathogen management options

Effective ICM includes proactive and reactive steps informed by risk knowledge and assessment (i.e. avoidance, minimisation, containment practices). Management and risk reduction measures are generally categorised as biological, chemical, cultural, physical and/or genetic. Examples are provided of each below; some suitable for routine adoption, while others are early innovations with no practical uptake to-date.

Biological – eg. mycoparasites, introduced antagonists, competitive avirulent strains, hypovirulent strains, rhizosphere microbial enrichment; suppressive soil community manipulation; clean, certified seed

Chemical – eg. synthetic pesticides (disinfectants, fungicides, insecticides), fumigants, seed and water treatments; naturals - volatile stimulants, biofumigation, systemic acquired resistance (SAR)

Cultural – manipulation of host and/or environment, eg. minimise introduction, spread, establishment, reproduction of pathogen; raise beds, delay planting, crop rotation; avoid host exposure to/contact with pathogen; roguing, inoculum reduction strategies, canopy management etc.

Physical/Mechanical – mulch layers; grafting, soil structure manipulation

Genetic – resistant or tolerant varieties, genetic engineering, conventional breeding

3.2 Enabling technologies in soilborne disease management

Practical and sustainable management of the key pathogens remains difficult. The R&D literature reviewed however, identifies enabling technologies that could increasingly be incorporated into new approaches in pathogen research and pathogen management. Their incorporation into RD&E efforts, farm practices and risk assessment is important. Some technologies have been adopted widely by the grains industries, and others are undergoing further development to increase their uptake, eg. by the potato industry. Enabling technologies for pathogen management are identified in recent reports (Mattiazzi, 2012; Donald and Porter, 2010; Villalta and Porter, 2010; Conde *et al*, 2010). They include:

- *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.
- *DNA-based diagnostic and rapid screening tools* - molecular diagnostics technology for multiple pathogens and nematodes; utilised also in inoculum density and reduction R&D
- *New systemic chemistry* – control/protection against systemic pathogens. Useful management tool; useful in research on efficacy duration of seed coatings.
- *Chemical resistance screening.* Essential component of chemical assessment that underpins regional chemical protection. Economies of scale possible through managed, regular testing and database maintenance.
- *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.

Gene technology has the potential to increase the rate of screening of genetic material (eg. 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.

- *Precision agriculture* - Guidance and GIS mapping/positioning technology
- *Precision irrigation technology* – application and monitoring
- *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.
- *iPhone applications and software platforms* – for monitoring and data management; knowledge and resource updates

3.3 Management options in Australia - What we already know

Australian RD&E has produced valuable information and identified numerous practices that have the potential to assist growers who are managing soilborne diseases in vegetables. Many practices however are not adopted routinely. Those that are regularly considered, to various degrees of sophistication, in decision-making or utilised in disease management on-farm (for key soilborne diseases) are highlighted in Table 6 [green]. Table 6 also includes available information and identified practices that appear to be irregularly included in decision-making, IPM or ICM, by growers. These information areas and practices that warrant continued pursuit (eg. through extension efforts, further development) for on-farm acceptance are highlighted in [salmon].

Table 6 : Identified management options for key soilborne vegetable pathogens

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*

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
Water moulds – *Pythium* spp. and *Phytophthora* spp. Key pathogen because – Often in complex with *Fusarium* spp. and *Rhizoctonia* sp. Wide host range In most cultivated soils Environmental influence high – esp. water	Stress reduction - manage fungus gnats in g/house	Cultivars - tolerance known, but not in all crop types *	Fumigation- metham effective for seedling problems
	Identify, utilise suppressive soils – for disease complexes	Clean transplants; nursery practices that recognise pathogen complexes	Fungicides – good range of seed, pre-plant and post-plant options
	Soil physical structure – CTF influence on porosity, bulk density, infiltration and host and pathogen	Microclimate manipulation - Irrigation, drainage and run-off management; raised beds	Systemic fungicides available
		Microclimate manipulation - soil temperature – plastic colour, planting time	

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/Physical	Cultural	Chemical
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 /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	

Sources: listed in Appendix 1

* Prioritise screening targets and market necessities. Tolerance as useful as resistance on some hosts for some pathogens (eg. nematodes)

It is apparent from the above that vegetable growers in Australia are not lacking in options for the management of soilborne diseases, but few are reliable and effective in all farming situations. There are more cultural practices, than chemical or biological practices available to growers for incorporation into their farming systems. Many warrant further development. The principles and sustainability benefits of biological control agents (BCAs) are generally understood by growers, but there are very few commercial options that can be confidently used. Their increased uptake would require serious research, development and extension efforts. Tolerant/resistant cultivars and synthetic chemicals are relied upon, where available.

3.4 Soilborne disease management options – USA

Vegetable growers in the United States also have vast amounts of information available to them on the management of soilborne diseases. The following table summarises practices they are reported to include regularly [green] and those that appear under-utilised but worthy of renewed attention [salmon]. It is clear that USA growers have very similar options for ICM to those of Australian growers. They have more synthetic chemicals and BCAs registered for use but it is my understanding few growers are reliant on BCAs because knowledge of their efficacy under different disease pressure, is not well-documented. Widespread use of BCAs is unlikely in the near future. A partial list of some USA-registered BCAs is included in Appendix 2B.

In California, nematodes are of less routine concern than they are in some Australian production locations, but diseases caused by *Verticillium* spp. are more extensive. This has resulted in greater RD&E efforts and awareness in California of inoculum-dependent diseases and the value of pre-plant knowledge of inoculum levels, and site avoidance as an economic risk management tool.

Table 7 : Identified USA management options for key soilborne vegetable pathogens

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	

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	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™ 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.

3.5 Other soilborne disease management options – Australia, USA

From the above, it is clear that soilborne disease management today utilises cultural practices and chemicals predominantly. Cultural practices alone however are insufficient to manage any of the diseases, once established. Risk assessment pre-plant is therefore a necessity, and DNA-based tools are being used in risk assessment by some growers, eg. with pathogen populations quantified pre-plant, and knowledge of inoculum density-disease incidence relationships, informed decisions on the suitability of the site and/or cultivar choice can be made.

3.5.1 Grains industries

The grains industries have invested in and adopted new risk-based approaches to the avoidance and management of soilborne pathogens, especially nematodes, *Fusarium* spp. and *Rhizoctonia* sp., in no-till, dryland farming systems. The PreDicta B soil-based DNA assay was designed for southern Australian grain producers and the service may be accessed via accredited agronomists.

It quantifies before seeding, the presence of soilborne threats[1]. This information forms the basis of risk assessments by grain growers, and underpins their planting and crop decisions. In addition such assays have increased the general understanding of soil microbial dynamics, and the effect of soil and seasonal conditions on them. (SARDI PreDicta B).

The grains industry will also be a beneficiary of new seed treatments produced by Syngenta (See Section 5.1).

3.5.2 Processing potatoes

The processing potato industry has adopted the DNA soil assay technology developed by the grains industry and is developing knowledge packages that allow growers to assess the risk associated with soil inoculum, soil type, the environment and cultivar choice – across farming systems. The technology is capable of detecting and quantifying the pathogens that cause powdery and common scab, black dot, several anastomosis groups of *R. solani,* and two nematode species. The inoculum densities have disease predictive value for common scab, black dot, and *R. solani* in the subsequent potato crop. (Kirkwood *et al*, 2009; Tegg *et al*, 2010; Pung *et al*., 2007).

3.5.3 Cotton

The cotton industry in the USA has detailed the inoculum density-disease incidence relationship for two serious soilborne pathogens. *F. oxysporum* f. sp. *vasinfectum* (race 4) and *Verticillium dahliae* are inoculum density dependent pathogens. With confidence in soil sampling results, disease incidence may be predicted. Such knowledge has also underpinned the effective screening of cultivars for their *relative* tolerance in different soil types, under different disease pressure and environmental conditions. These defined relationships and cultivar knowledge have alerted growers to the arrival of new, aggressive strains of the fungus (new races). There are no effective chemical options for the control of Verticillium wilt once infection has occurred.

Site risk assessment and resistant cultivars have allowed the cotton industry to continue its growth in the USA (Hao *et al*, 2009), as has the success of Bt gene inclusion which has led to a significant reduction in pesticide use and commercial production losses. In Australia, the widespread uptake of the Best Management Practices (BMPs) has resulted in efficient water use, reduced pesticide use, and more sustainable production of existing and the development of new 'eco-cotton' cultivars. The adoption of the BMPs was increased by the water crisis and imposed water restrictions.

3.5.4 Avocadoes

This crop is susceptible to several soilborne pathogens, primarily watermoulds.

Phytophthora cinnamomi-suppressive soils were identified in the 1970s. Australian jarrah forests (in Western Australia) and avocadoes growing in some parts of the north east of Australian were found not to succumb to *P. cinnamomi* despite its presence and the hosts' susceptibility. Historically, long-term research on the nature of suppressive soils relied on the screening for soils for organisms that had antagonistic and/or mycoparasitic capability against *P. cinnamomi* under laboratory conditions. Today the DNA-based and soil profiling (eg. chaperonin gene) technologies suggest that the 'suppressive capacity' of a soil community may be researched and that biotic and abiotic influences (and their interaction) in response to pathogen populations, seasonal conditions etc. can be followed and characterised (Keen an dVancov, 2010).

---

[1] SARDI tests offered for Cereal cyst nematode, Take-all (*Gaeumannomyces graminis var tritici (Ggt*) and *G. graminis var avenae (Gga)),* Rhizoctonia barepatch (*Rhizoctonia solani AG8*), Crown rot (*Fusarium pseudograminearum* and *F. culmorum*), root lesion nematode (*Pratylenchus neglectus* and *P. thornei*), Stem nematode (*Ditylenchus dipsaci*), and *Mycosphaerella pinodes, Phoma medicaginis var pinodella,* and *Phoma koolunga*.

3.5.5 Mushrooms

The bacterium *Pseudomonas aeruginosa* is commercially-available to control green mould (caused by *Trichoderma harzianum*) in greenhouse mushroom production in sterile growing media. *T. harzianum* is itself a widely-researched BCA, but has provided variable results worldwide on a wide range of crops.

4 KNOWLEDGE GAPS

Most vegetable growers today are 'information rich', but (specific) 'knowledge poor'. Growers do not lack essential basic scientific information on key pathogens, but its relevance and utility for particular sites and cropping systems is not always clear. The results for example, of research conducted in greenhouses, or inoculated sites, in one soil type at low level disease pressure, do not necessarily translate to a field situation with a different soil type and host cultivar.

It is difficult for vegetable growers to integrate their knowledge of soil type, cultivar susceptibility, inoculum density, management options and potential environmental impacts, into a risk assessment that provides clear Go/No Go decisions. However, in the absence of risk-based decision-making, growers are limited to reactive responses to disease problems for which there are too few effective, sustainable, and economically-viable, post-plant control tools.

4.1 Whole farming system knowledge gaps

Many vegetable producers today require more specific risk assessment 'know-how' to inform and underpin decisions applicable to their whole farming system and individual crops within it. The knowledge required to avoid and minimise losses due to soilborne pathogens, is multi-faceted and complex.

"Whole of system" knowledge and enabling technologies have the greatest potential today to broadly increase capabilities, adoption, and success in soilborne vegetable disease management. This has been apparent in the Australian grains industries. The packaging of existing information in a format that addresses the whole system (*cultivar x pathogen x management x soil type x environment*) has improved risk assessment, production success and response capabilities.

Research, development and extension knowledge gaps exist.

4.2 Knowledge gaps in pre-plant risk awareness

Many growers 'know' their land and 'evaluate' their threats intuitively. Ideally pre-plant decision-making should rely on more analytical assessment of site risks, options and well-informed cropping system knowledge.

4.2.1 General pre-plant knowledge gaps

There is need for a readily accessible resource that comprehensively packages relevant scientific information (eg. pathogen biology, epidemiology) with relevant risk factors to be considered in planting decisions. These may include:

- Understanding of 'soil health' and how it might be influenced and evaluated
- Inoculum density-disease incidence relationships in various soil types
- Cultivar susceptibility in different soil types under different disease pressure
- Seed/seedling/planting material health and infection thresholds
- Economics of treatments/practices required to manage a 'moderate risk' site

The "*know before you sow*" concept relies on **pathogen** x **soil type** x **environment** knowledge to underpin planting decisions on both **crop/cultivar** and **management** options. Many growers underestimate the value of informed pre-plant decisions. Examples of potential responses of growers to multi-faceted knowledge that can inform pre-plant decisions, are provided below:

- ***Site selection or avoidance***

  Pathogen target – block/farm history, previous crop, pathogen presence; inoculum density-disease incidence and economic thresholds for sustainable production; primary inoculum sources.

  Soil type and texture - effect on pathogen, beneficial, arthropod density, movement, management. Soil physical structure – effect on plant growth, root depth, infiltration rates etc.

  Soil community and health - eg. known buffering/suppression capacity.

  Environment – soil 'micro-environment' effect on pathogen and beneficials, host plant emergence and development; cultivar options etc. 'Macro-environment' – temperature, humidity, rainfall patterns and conditions – effect on disease development.

- ***Site preparation***

  Pathogen target – inoculum reduction potential; response to organic matter amendment and retention, biofumigant crop incorporation; fumigation effects, options; weed and volunteers as alternative hosts; row direction, drainage, infiltration, plant spacing, raised beds etc. to minimise pathogen conducive conditions.

  Plant growth potential – effect of prior chemical use (esp. herbicides), weeds/volunteers (as competitors for resources); chemical, nutritional and 'structural' amendments (fumigants, mulches, organic matter, gypsum); tillage.

- ***Planting material choice***

  Pathogen target –tolerant/resistant cultivar options; plant density variation, plant architecture features (that limit conducive conditions or infection sites); susceptibility period avoidance (via planting dates); form and quality of planting material – transplants, seed, grafter seedlings; coated seed, treated tubers etc.

  Plant growth and productivity – economics of commercial, rotation/break crop, fallow in different soil types, under different pathogen pressure.

- ***Management options***

  RISK - Pathogen x soil type x environment x crop

  - *High* – no management options reduce threat sufficiently; do not plant susceptible host. Plant alternative crop with some economic return? Or leave fallow?
  - *Moderate* – options to manage risk: plant later, different cultivar, increase spacing, chemicals available for seed treatment etc. Subsequent economic assessment of options will influence decision to plant/not plant
  - *Low* – plant clean material to maximise returns

Implicit in these decisions is awareness of the option '*not to plant*' a site. This is not always a financially-viable option for vegetable growers who may not be able to move sites, or accommodate a fallow period. However in reviewing 'management of soilborne pathogens', the choice of planting site is a basic and very important initial decision, and it should be based on informed risk assessment.

4.2.2 Inoculum density-disease incidence relationships and thresholds

Inoculum density-disease incidence relationships for some seedborne bacteria and soilborne pathogens, eg *S. minor* and *Sclerotium* spp., have been established for some hosts, in some locations. The practical value of such scientific data and in risk assessment, are increased when cultivar and soil type interactions, and economic thresholds, are integrated. The significance of risk associated with several soilborne pathogens of potatoes has been determined in Australian soil, as 1000 pg DNA/g soil *Sp. subterranea*, 200 pg DNA/g soil for *S. scabiei*; 25 pg DNA/g *R. solani* AG3 and 100 pg DNA/g soil for AG2.1 (Kirkwood *et al*, 2009). There are knowledge gaps in this area however, for most ‘key’ soilborne pathogens on other hosts. Research is needed to determine more soilborne pathogen economic thresholds, and integrated knowledge of risk factors - *pathogen x crop x soil type x environment.*

Similarly, risk assessment associated with practices that target inoculum reduction (eg. by biofumigant crop, deep-ploughing, chemical fumigants, melanin production restriction, volatile stimulant delivery etc.). The economics of the practice and the effectiveness of reduction, must be known, yet it is a knowledge gap in most farming systems (McDougall and Orr, 2011; Villalta and Porter, 2010; Villalta and Trapnell, 2010; Villalta *et al*, 2010b,c).

The scientific principles of ‘effective’ crop rotation are understood more widely in terms of “soil health”, than in specific pathogen management or economic terms. The economics of cropping sequences and their collective impact on pathogens over time, are not well-documented. In potatoes *R. solani* thresholds for example, differ by anastomosis group and inoculum source. The soil population is influenced by rotation crop sequence and therefore should be quantified after each crop. The cumulative inoculum reduction is of relevance to the next potato crop. A fallow period in some situations may be the most economic means of inoculum reduction, but not a viable option within the farming system; the inclusion of a biofumigant crop in rotation may be economic for lesion nematode management but less so where root knot nematode is the problem. Similarly, a 50 percent reduction in sclerotia may not reduce the productivity risk at sites with high initial populations and a susceptible host. (dal Santo and Holding 2009c; VicDPI factsheets, 2010).

4.2.3 Specific knowledge gaps – pathogen specific

The pathogens identified as ‘key’ pathogens in Australian vegetable production have specific knowledge gaps that limit their effective management.

Table 8 : Pathogen specific knowledge gaps relevant to disease management

Pathogen	Knowledge gaps
Sclerotinia spp.	• inoculum density-disease severity relationships in different soil types • economics of inoculum reduction –biofumigant crops, stimulants, melanin inhibitors • economics of rotations – biofumigant, fallow and cumulative effect • cultivar performance under different disease pressure • critical wetness periods (irrigation and environmental conditions) – and their predictive value • fungicide resistance and cross-resistance problems on regional basis
Rhizoctonia sp.	for some hosts: • source of primary inoculum • relative threat of seedborne +/- soilborne inoculum • inoculum quantification and thresholds • impact of soil type and crop sequence on inoculum reduction • impact of organic amendments on inoculum reduction over >1 season • effective chemistry

Pathogen	Knowledge gaps
Fusarium spp.	• effective systemic chemistry • cultivar resistance for *Fusarium* in disease complexes • economics of grafting on high value crops • relative effectiveness: anaerobic soil disinfestation x soil type x pathogen • effective fumigation alternatives
Water moulds	• effective seed treatments • fungicide resistance management • characterisation of 'cross-genus' (> one pathogen) suppressive soils • soil moisture impact on all pathogens in the complex
Nematodes	• quantified nematode thresholds (and reduction) x soil type x crop sequences • tolerant vs resistant cultivars and impact of resistant crop on soil microbial balance (eg. of *in situ* fungal parasites of nematodes; pre-plant and pre-harvest populations of pathogens in complex with nematodes) • characterisation of nematode suppressive soils

4.2.4 Specific knowledge gaps - Pathogen complexes

- the microbial ecology of key pathogen complexes, in different soil types
- dominant pathogen processes and sequences in colonisation and infection in 'complexed pathology'
- systemic chemistry with cross-pathogen genus efficacy
- crop rotation effects on all pathogens to which host is susceptible
- cross-pathogen genus suppressive soils

Rhizoctonia, *Pythium* and *Fusarium* spp. in complex, and *Fusarium* spp. and nematodes in complex, often cause significant losses in vegetables. The influence of environmental and soil conditions, rather than inoculum density (unless seedborne), appear to complicate their combined management.

Pathology research has rarely targeted 'the complex'. However solutions for 'complexed pathology' have at times been revealed through the elimination of one component of the complex, eg. "virus-free" garlic (cleaned up through meristem tip culture) is less prone to stem and bulb nematode infestation and Fusarium basal rot infection, over several field generations (Crowe, pers. comm.).

In contrast, single component research can be derailed by the "complex pathology" if the ecology and infection processes and sequences are not understood. This knowledge gap is particularly relevant for 'damping off' disease complexes where water management may minimise the impact of *Pythium* spp. but increase seedling losses attributed to *Fusarium* spp. Effective nematode control in capsicums resulted in increased *Pythium* and *Rhizoctonia* losses, in a particular soil type (Stirling, pers. comm.).

The knowledge of potato disease complex ecology being developed by the processing potato industry will have relevance to several other vegetable industries. It may allow the identification of suppression effective against multiple pathogens (cross-genus suppressive capacity), in some soils.

4.3 Technology knowledge gaps

4.3.1 Quantification and characterisation of specific soil microbial communities

The vegetable industries other than potatoes are yet to make good use of DNA technology and related services. Awareness of the technology and confidence in using its outputs to guide planting decisions is needed in the vegetable seed and production industries.

4.3.2 Controlled traffic farming principles

The awareness of this technology and its impact on general soil health is limited amongst vegetable growers. There are technical impediments to CTF adoption by vegetable industries that have retained tillage as a primary bed preparation activity, and use contract machinery (eg. for harvest). The diversity of crops within a vegetable farming system, the difficulty of machinery integration (esp. to a common wheel width), and the relatively small block size contribute to the negligible adoption of CTF in vegetable production.

CTF principles and technology, and their integration with GIS mapping/positioning and guidance technology, are established and widely understood in broadacre farming. The benefits of CTF technology in pathogen management in vegetable production are yet to be fully tested, but the general soil benefits of CTF are likely to have some positive impact on pathogen management, i.e. reduced compaction improves soil structure, porosity, infiltration rates; soil-water relations, root growth and nutrient uptake. Soil biological activity is enhanced under CTF and earthworm activity research has demonstrated this. In terms of economics, vegetable growers would value the reduced input requirements (eg. fertiliser, water) shown to result from CTF (Tullburg *et al*, 2007; McPhee, pers. comm.; Controlled Traffic Farming – adoption in vegetables, not dated).

4.3.3 Monitoring and data management

It was recently found in a technology survey of 700 grain growers, conducted by Grain Growers Limited and NSW DPI (Grain Growers Limited, 2012), that smart phone technology is not a high priority knowledge source, for many grain farmers. Vegetable growers are likely to be similar, but they are encouraged to adopt such technology as it has the potential to assist with accessing and storing data, risk assessment (i.e. data on block history; inoculum density) and management, at specific sites.

In some countries, annual crop growers have available to them, sophisticated tools for accessing specific information, and recording and receiving data associated with their specific sites, eg. iPhone applications, iPad devices attached to tractors or hand-held. In the United States for example, the Integrated Farming Systems^{SM} Platform (Monsanto) utilises sophisticated software and hardware to capture annual data from growers on *seed genetics x on-farm practices x environment*, in *yield management zones* that are differentiated by planting and nutrient systems. Similarly, FieldScripts^{SM} (Monsanto) advises corn growers of the optimal row spacing, hybrid and seeding rate for their specific management zone (Monsanto).

4.3.4 Genetic manipulation/engineering

Although not widely accepted technology in Australian fresh food to-date, gene technology cannot be ignored in any effort to advance the management of soilborne diseases. Resistant and tolerant cultivars developed via gene manipulation, are likely to be the sustainable long-term solution for several key soilborne pathogens.

5 CLOSING THE KNOWLEDGE GAPS

The nature of the knowledge gaps limiting the capacity of growers to assess the threat of soilborne diseases in their farming system, have been considered. Many grower knowledge gaps do not relate to lack of information, but rather to its synthesis and transferability across farming systems.

To close knowledge gaps, research, development and extension efforts are required. It is recognised that efforts in extension particularly would yield practical and timely increases in grower capabilities in disease management. Extension priorities are discussed further in Section 6. Research that provides knowledge to underpin risk assessment and response capacity, and the development of several management tools, is also necessary.

5.1 Gaps closure requiring further research and new knowledge

5.1.1 Researching disease complexes

The 'whole of system' relevance of research on individual pathogens on a single host, is unclear in most research reports. Research on *Fusarium*, *Rhizoctonia*, *Pythium* spp. and nematodes collectively is likely to result in more transferable knowledge, especially when integrated with specific knowledge of soil type, seed health, seed treatment, soil conditions and previous crop history.

Linking pathology, breeding (and screening) programs, and integrating high yield cultivar research with soil health and microbial community quantification and characterisation are likely to enhance the outcomes of new cultivar knowledge. There is evidence from sugarcane and grains research that multi-disciplined, research teams (eg. that include agronomists, pathologists, water relations expertise, agricultural engineers) usually deliver integrated and practical approaches to complex problems.

Villalta and Porter (2010), Kirkwood (2009) and Stirling (2012) are experienced in such integrated research and its expansion to include more pathogens and nematodes, soil types, DNA quantification technology, and team specialists, is warranted.

5.1.2 Economic thresholds

In pathogen-disease relationships for which no threshold has been established, one cannot reasonably evaluate risk or the potential economic benefit of management options. More inoculum density-disease incidence research is required on inoculum-dependent soilborne diseases. It will require the integration of pre-plant inoculum density quantification research with disease incidence by soil type and cultivar. Ideally it would also integrate data on the microbial soil community characterisation of high yielding and low yielding relationships within the research trials.

Villalta has led various projects on the economics of treatments and management practices. This work is most useful when combined with inoculum density knowledge and soil type and cultivar susceptibility data (McDougall and Orr, 2011; Villalta and Trapnell, 2010; Villalta and Porter, 2010, Villalta *et al*, 2010b).

5.1.3 Inoculum detection and microbial community quantification

The value of high throughput DNA sequencing and soil profiling/fingerprinting technologies to vegetable growers will be greatly enhanced when the detectable range of pathogens and effective beneficials, is increased and their relative presence (quantified) may allow prediction of high (or low) soil-crop-environment productivity. The categorisation of soils as suppressive or conducive is an anticipated future benefit of such research. When suppressive capacity can be readily identified and characterised, it will be a risk management tool with the potential to deliver long-term solutions to some soilborne pathogen problems.

The vegetable industry is a beneficiary of pioneering research investment made in these areas by medical and veterinary industries and its further development in agriculture by the grains industries. The medical industry research demonstrated the benefits of ‘probiotics’ in human health. The selective ‘enrichment’ of soils and plants to promote or create suppressiveness, has potential and warrants Australia-based research to extend the chaperonin gene work undertaken in potato soils of Canada (Edwards *et al*, 2011; Keen and Vancov, 2010).

The understanding of microbial fate can be greatly increased by the use of this technology. The short-term and longer-term fate of BCAs applied on seeds, or introduced to soil, will greatly assist progress on soil amendments and manipulation of microbial communities in soil. Research on enrichment delivery and the influence of soil chemistry on sustained enrichment, is premature but may warrant early scoping investigations.

5.1.4 ‘Seed’ health and quality evaluation

Despite such R&D being largely led by international seed companies, the Australian vegetable industries can be influential in demanding higher quality seed and reporting on seed sources and health evaluation parameters.

Seed quality is a risk and biosecurity factor about which growers have little knowledge or control. Clean seed (and planting material generally) is paramount to reducing disease establishment problems and prevention of introduction and movement of pathogens into production areas. Nursery industry input to research on seed health determinants, rapid seed screening technology and certification protocols, is required. Seed treatment is a current research focus in USA for vegetables and grains[2]. It reflects a trend also seen in Australia, of increasing preferences for seed planting rather than transplanting. In Australia, this is particularly visible in the spinach, lettuce and Asian vegetable industries, as their crops are susceptible to multiple pathogens and have very few control options.

5.1.5 New chemistry and ‘combined actives’ crop protection

The loss of access to synthetic chemicals and fumigants used in vegetable production has made production more difficult in some locations, and has allowed several previously-managed pathogens to ‘flare up’ (eg *Macrophomina* sp.). New synthetic chemistry research and development is the domain of crop protection product manufacturers and innovative private operators (eg. volatile stimulant manufacturers) who are today increasingly screening biological organisms also as sources of effective genes and metabolites with crop protection properties. New chemistry relevant to the key pathogens is likely to have several of the following characteristics: systemic activity but with negligible threat of persistent residues in soil or produce; potential for drip-application; potential as a seed protectant or pre-plant treatment. (Donald *et al*, 2010).

5.2 Gap closure requiring further development of existing knowledge

Industry development needs in the area of risk assessment relevant to soilborne diseases, are discussed below.

[2] Syngenta has reported that its $1billion pa global R&D is soon to generate rewards for Australian farmers with a new innovative seed treatment pending regulatory approval here. *Vibrance* has a new active ingredient to provide protection for emerging cereal crops against a range of common soil diseases including Pythium root rot and *Rhizoctonia* sp. (Sygenta, 2011)

5.2.1 Research output classifications

Few research reports clearly distinguish *early innovation* positive results, from those outputs that require further *development* or ‘ready-to-adopt’ *solutions*. The assignment of an “adoption stage” classification (eg. *early innovation*, *advanced innovation*, *early development*; *advanced development*; *specific adoption-ready*; *commercial adoption-ready*) is recommended.

Such a system of classifying research outputs, would simplify the synthesis of the vast amounts of research information to which growers are exposed, and allow them to focus on relevant strategies and tools that can be confidently incorporated into their farming system. Vegetable industries and HAL would also benefit as the ‘further development’ needs and opportunities would become clear. Ready-to-adopt solutions should be aligned with risk assessment, and therefore incorporate knowledge of soil type, pathogen pressure, and cultivar impacts on performance, in various farming systems and locations.

5.2.2 Resource access made easy

The volume of soilborne disease-related information available to vegetable growers is overwhelming, and remains difficult to scan and mine. Growers require in addition to hard copy information packages, a co-ordinated, well-indexed resource that is regularly updated. A searchable database exists (from the IPM Coordination project -*VG09191*) for AUSVEG members, but grower-friendly guidelines are needed to explain how to access specific information, eg. key words, disease/pest common and scientific names, symptom types etc. At present, accessing information on sustainable practices for lettuce disease management requires AUSVEG user codes (username and password) and knowledge that the details are held within the “technical insights” area, followed by “IPM”. From this, useful information within ‘*IPM and Chemical Database for field lettuce and celery*’ may be found.

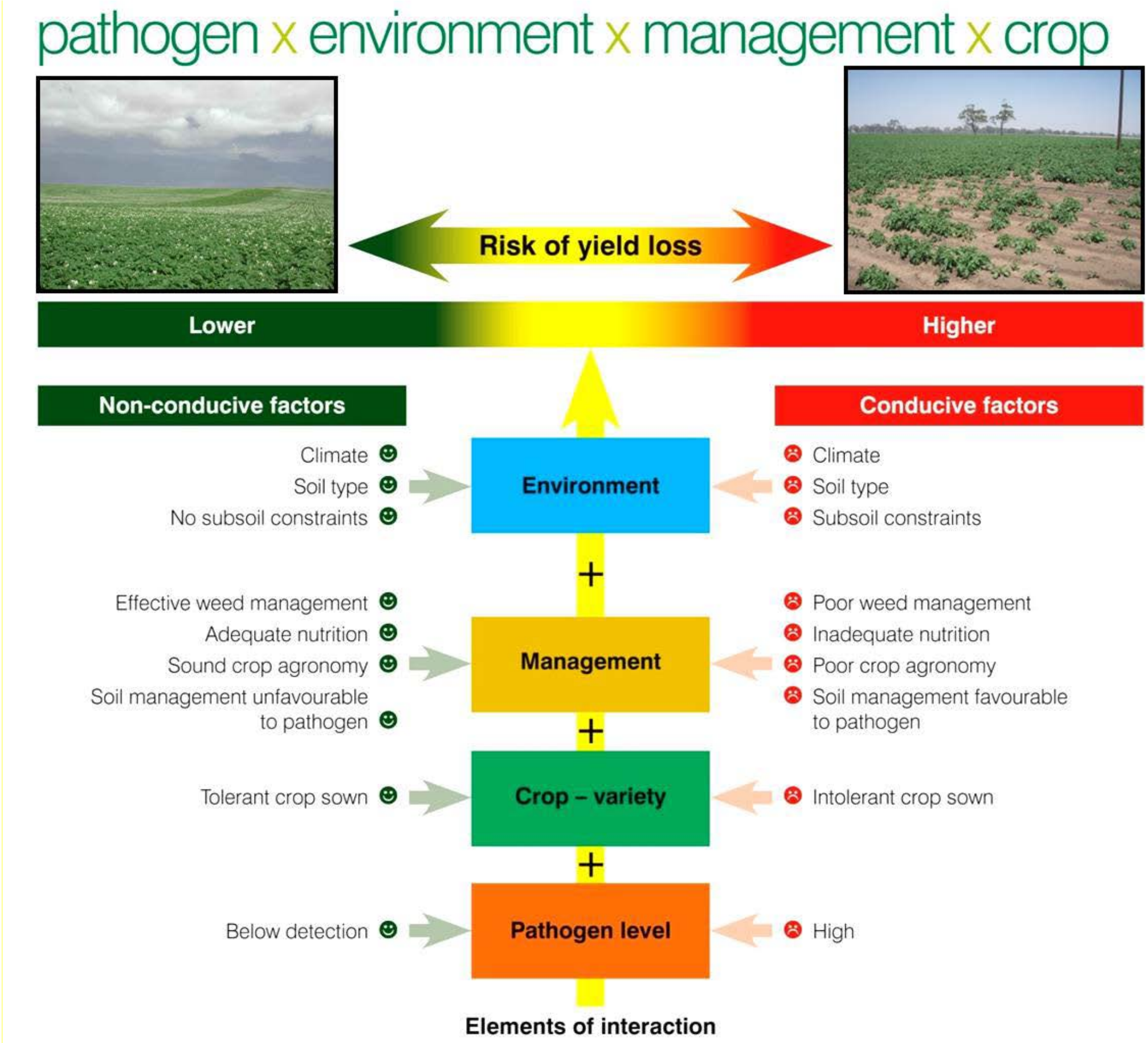
In the recent Grain Growers Limited survey (2012), electronic mail (e-mail) was the information technology preferred by 98.3% of respondents. It was also the method preferred (89.7%) for delivery of industry news. Knowledge of vegetable grower database searching capabilities, and preferences are not well defined; nor are their information delivery preferences. A technology survey similar to that recently undertaken by Grain Growers Limited (2012) would provide valuable industry development insight.

Key word preferences should guide database indexing and helpful cross-indexing. It is for example, likely that growers searching disease information will search by the disease common name rather than by the scientific name of the pathogen, but both require listing and cross-linkage. Risk factors need definition and a glossary of risk assessment and pathology terms would be valuable. Information technology specialists are qualified to drive such development projects, but grower, consultant, industry development officer input, is essential.

5.2.3 Integrated risk assessment in practice

Demonstration trials in different soil types and under different inoculum pressure are needed for growers to evaluate the relevance of research on non-chemical and chemical approaches to pathogen management in their growing environments and cropping systems. The development of a ‘whole of system’ populated risk chart would be valuable to other vegetable growers. A suitable framework is currently under development (draft form) for the processing potato industry (Figure 1). Decision support charts for regions (eg chemical protection and choices) and/or host-specific pests (eg. phylloxera in grapes), chart may be appropriate. Examples of simple ‘decision assistants’ (eg. rootstock decisions, varietal susceptibilities) are included in Appendix 3.

Figure 1 : Disease Risk Interactions to inform cropping decisions (DRAFT)



Source: Draft - Australian Potato Research Program 2, 2012

5.2.4 Regional chemistry protection and resistance management

Coordinated, harmonised chemical protection strategies need an associated education program and further development at the regional level. Practical regional resistance strategies should outline the principles of sustainable and effective use of the chemicals at risk, the impact of timing, rotations, and coverage, relevant for all crops and cropping systems in the region that use similar chemistry. Additional industry and regional benefits and economies of scale may be derived from the coordinated and systematic submission of pathogen samples to a central horticulture facility that also has the capacity to manage a database of results. (Hailstones, 2011; VicDPI factsheets, 2010; dal Santo and Holding, 2009).

5.2.5 Chemistry evaluation

Synthetic and soft chemical options and seed treatments require testing under different disease pressure, in different soil types, on the range of commercially-acceptable cultivars. Nationally-coordinated, APVMA-compliant evaluation trials are recommended. Nurseries must be included in more evaluation of seed, seed chemistry and treated seed.

5.2.6 Farm records software

Data storage (and access) tools are available. Hortus for example has a software product available to industry (http://hortus.net.au/products-software.php), but vegetable growers have not generally been ready adopters of software technology for data management.

A concerted effort to increase the uptake of such technology by the vegetable industries should not be delayed. The introduction and presentation of such technology is best conducted as an industry development activity in partnership with manufacturers. Case studies on applications, hands-on demonstrations, no-obligation trial periods, data entry and interpretation assistance should be provided with feedback required from recipients. In a development activity of this kind, it is hoped that early adopters will see an investment return that motivates championing of the technology through a designated commodity group or region.

Biosecurity and quality assurance (QA) requirements and market access and trade negotiations are increasingly assisted by evidence of monitoring, demonstrated pathogen absence, and systems approaches to pest management - even as outputs from simple data storage devices. Regulators and marketers also are therefore important in driving the uptake of such technology.

The respondents to the Grain Growers Limited survey (2012) identified 'spray record keeping' and 'paddock record software' as two of their top three new development priorities, which suggests the existing tools may require further development to satisfy all farming systems.

5.2.7 Nursery engagement

In the area of disease management, vegetable industry sophistication will proceed at a faster rate with greater nursery engagement and contribution. The impact of seedborne inoculum remains largely unquantified in most Australian vegetable systems, but it has the potential to increase the impact of soilborne inoculum and complicate disease management. The threat associated with some seed host-pathogen interactions (eg. potato spindle tuber viroid and tomato seed; seedborne viruses), extends well beyond the initial seed crop. A regional threat, about which growers have little awareness and no control, may be created.

Nursery capabilities, standards, and practices influence the subsequent crop potential and it is recommended that seed companies and nurseries provide to their customers more detail on seed source/s, evaluations, seed batch numbers, treatments, and relevant traceability indicators (for seed, soil mix/media, germination dates etc.). It is also recommended they retain some seed from each seed lot in the event of a seedborne disease outbreak or incursion.

5.2.8 Detection and diagnostic services

Good diagnostic tools are available for diagnosing the key pathogens in infected plants, but the full range of detection and diagnostic services available to vegetable growers is not readily apparent to all growers. In order to effectively manage risk, pre-plant detections are more valuable than post-plant diagnostics, especially in situations where pathogen detection levels have a verified correlation with subsequent disease development.

Pre-plant detection of multiple pathogens within microbial communities (soil) or on seed, is a more recent commercial reality, and practical risk assessment tool. Multiplexing offers the potential for more efficient and cost-effective screening of soils. The technology, sampling procedures and inoculum density-disease incidence evaluation across cultivars, cropping systems and soil types, require more development and integration, to ensure utility of the services in risk management, beyond the processing potato and grains industries.

The fate of pathogens or food safety contaminants may be mapped using this technology, thereby providing very useful data on the actual risk associated with the microbes in the presence/absence of other microbes or synthetic treatments. With further development, there is potential for such assessments post-harvest and in conjunction with pesticide residue testing.

To optimise the benefits of available services, best practice sampling protocols require further development or upgrade. The potato industry and HAL have invested in such development and the APRP2 work has identified best soil sampling strategies and the necessary number of tubers to be sampled and the time of their extraction from a run (Tegg *et al*, 2010).

5.2.9 Controlled traffic farming

Although not developed sufficiently for systematic vegetable grower adoption, CTF technology is available and demonstrations of it in vegetable industries have the potential to rapidly increase vegetable grower awareness of the benefits of reduced traffic on plant health. It is the opinion of this reviewer that co-ordinated, demonstration CTF trials would be of considerable educational value. They would be useful training sites for integrated soil management capabilities, and the general benefits of monitored and reduced traffic (Controlled Traffic Farming – adoption guidelines for vegetables). The potential for soil compaction in vegetable farming is highlighted by the figure included in Appendix 3.

5.2.10 Tolerant and resistant cultivars – co-ordinated national, rapid screening

It cannot be assumed that internationally-bred vegetable cultivars will perform in Australia, as elsewhere. Proactive, local collaboration of pathologists, breeders and seed companies in early cultivar screening (traditional or utilising molecular markers) is likely to deliver industry benefits. Evaluation trials should be coordinated within a national protocol and conducted across a range of defined soil types and disease pressures. The potato industry is leading in this area with the integration of breeding and pathology programs and the screening of 'potentially resistant/tolerant cultivars in advance of anticipated entry of exotic pests that will challenge the economic viability of existing cultivars.

6 EXTENSION - ADOPTION AND IMPLEMENTATION

Despite identifying research and development knowledge gaps that warrant further attention, it is the author's opinion that vegetable growers today will benefit more significantly from increased investment in the extension of specific knowledge and transferable outputs from previous research. Targeted extension efforts combined with appropriate delivery systems have been identified as the priority investment area, with the adoption of systematic risk assessment steps and reduced soilborne disease impact, being indicators of success.

The adoption of new practices by the vegetable industries has often been considered unnecessarily slow. The uptake of recommended practices from the 'stocktake report' (McDougall, 2007) has reportedly been limited (pers. comm. HAL). While the specific reasons are not known, they likely include: the outcomes cannot be relied upon, are not fully developed, are impractical to implement, or growers are lacking the know-how and confidence to adopt the practice.

McDougall analysed IPM adoption and identified the 'lack of a crisis', the paucity of consultants available to personally assist growers, the up-front economics (as opposed to cost-benefits in longer term) of IPM, and confidence in results, as explanations for the limited uptake of IPM by some vegetable industries. She also identified the most important drivers of IPM adoption as:

- Reduced cost; fewer sprays
- Improved disease control
- Chemical loss – resistance (and cross-resistance)

- Chemical loss - de-registration
- Public image

In general, disease management advice assumes "basic" knowledge and competency. These 'basics' are assumed to motivate appropriate responses by primary producers, that indicate risks are understood and minimised. This review of recent research reports has revealed that many options for disease management are not practical or ready for on-farm adoption with confidence, and that the capacity of some vegetable growers to respond to, or influence risk, is limited. Table 9.

Table 9 : Knowledge underpinning effective risk assessment, response and capacity to influence

Disease management basics [x]	Examples of expected grower activity/response	Demonstrated capacity to influence
Know your risk 'before you sow'	Integrate assessment of threats, priority critical steps; utilise pre-plant services to identify soil populations; understand impact of prior crop and block history; soil type; cultivar choice; → avoid poor sites.	Limited
Hygiene and sanitation	Assess relative benefit and risk of organic material – green waste hygiene vs organic amendment? biofumigant crop timing; removal of rogue plants; soil/equipment/water/vehicle movement etc.	Medium
Avoid/exclude	Apply risk assessment steps to determine risk associated with planting cultivar in soil type etc. →avoid high risk sites/crops.	Limited
Protect host	Site preparation, planting time, injury minimisation, attention to soil health; traffic limitations.	Medium-High
Remove alternate and volunteer hosts	Weed control and volunteer control.	Medium - High
Clean 'seed', seedlings, plant material (transplants)	Assess and request quality planting material knowledge; record batch details etc.	Limited
Monitor early plant health	Distinguish health issues attributable to planting material quality and/or subsequent infection. Walk crops, note distribution of problems, rogue.	Medium
Understand irrigation influence	Manipulate wetness periods, infiltration etc. to favour host, not pathogen or pathogen complex.	Medium - High
Understand chemical options	Resistance management; rotate chemicals, good coverage, effective timing of applications; plant-derived/soft options	Medium - High
Observe/record problems	Record keeping by block and whole of farm.	Limited - except for spraying
Identify problems correctly	Sample correctly, use available services.	Limited-Medium

[x] Adapted from FreshLogic website 2011

6.1 Available resources and learning opportunities

There is no shortage of relevant pathology information available to growers. Growers have access to large volumes of information on key pathogens. They do not necessarily have this available in a format that is easily interpreted. Growers cannot always identify the practical potential or implications of new information, its readiness for adoption, or its suitability for their farming system or location.

It is this author's view that growers today require co-ordinated, packaged information that increases their capacity to identify and respond to risks associated with soilborne diseases. An 'adoption stage' categorisation for R&D outputs would divert on-farm attention from under-developed innovations, toward ready-to-adopt options, about which there is justified confidence based on extensive prior testing in relevant farming systems.

6.1.1 Delivery preferences

The preferred delivery format for information, and engagement strategies of growers themselves, are not as well understood for vegetable growers as they are for grain producers. In the recent survey of 700 grain growers, delivery through accepted and accessible routes was preferred over advanced technology delivery, eg. 43 percent of respondents reported they had no intention of purchasing a smart phone, despite recognising its capabilities for data access.

The opportunity for vegetable growers to provide similar input to the industry and HAL is yet to be presented, but it is my experience that for complex information, printable/hard copy summaries in the form of factsheets etc. are a preferred output of all projects with '*ready-to-adopt'* solutions to disease problems. All documents must be dated, suitable for collation (and subsequent replacement) within a folder, and be limited to adoption ready information and tools.

6.1.2 Resources for key pathogens

Key resource formats for vegetable pathology information include:

- **Best practice guides** eg. dal Santo and Holding 2009, 2009b-d.
- **Ute guides** and **on-Farm Manuals** (eg. by Plant Health Australia-PHA)
- **Factsheets** eg. VicDPI Factsheets, 2010.
- **Books** +/- DVDs eg. Persley *et al*, 2010; Badgery-Parker, 2009; Koike *et al*, 2006; Compendium of diseases (various) APS, USA.
- **Websites and web-based data –** Bureau of Meteorology (BOM); UC IPM; Cornell IPM; AUSVEG; subscriber advisory services
- **Reports –** Comprehensive HAL reports eg. Hailstones, 2011; Donald and Porter, 2010; Villalta and Porter, 2010; McDougall, 2007; Porter *et al*, 2007a,b)
- **Posters, meeting proceedings,** eg. *Sclerotinia* and *Sclerotium* trials: http://www.peracto.com.au/resources/sclerotinia-poster.pdf.
- **Face to face –** in-person (workshops, field days, roadshows, demonstrations)

  Face to face – distant (webinars, video links etc)
- **Phone applications**
- **Quality Assurance** and **Food safety** requirements and manuals

6.1.3 Best practice guides

There are several examples of industry information released as Best Practice Guides or comprehensive factsheets. While valuable at the time of release their 'effective life' is limited. All such documents must be dated and it is my recommendation that they focus on 'ready-to-adopt' information rather than early innovations or alternative practices that have not been demonstrated as effective or practical across a number of soil types or environments. Existing examples of factsheets and Best Practice Guides are:

- VicDPI Factsheet. 2010. Managing Soilborne Diseases in Vegetables (component of Villalta and Porter, 2010).
- VicDPI Factsheet. VicDPI. 2010. Managing Sclerotinia Diseases in Vegetables. (component of Villalta and Porter, 2010).
- Vic DPI Factsheet. 2010. Improving Soil Health for Yield and Profit in Vegetables (component of VG07008)
- dal Santo, P. and R. Holding. 2009. Best Practice for Vegetables. Good Agricultural Practices (GAP). HAL Report and factsheets VG07109.

- dal Santo, P. and R. Holding. 2009b. Best Practice – Fusarium, Pythium and Rhizoctonia Root Rots in Vegetables. 20pp. (component of HAL VG07109).
- dal Santo, P. and R. Holding. 2009c. Best Practices – Sclerotinia in Green Beans. 21pp. (component of HAL VG07109).
- dal Santo, P. and R. Holding. 2009d. Best Practices – Sclerotinia in Lettuce. 22pp. (component of HAL VG07109).
- Best Practice IPM strategies *in* Donald and Porter, 2010 (Appendices to VG07125).

The uptake of these documents as guides in decision-making, or practice implementation, cannot be determined from the information available. It is likely they have been read as they are short, comprehensive summaries and their format is appealing. However, they include some information that is now outdated; and results of innovative work not ready for adoption is not distinguished clearly from adoption-ready, fully tested knowledge.

Examples of decision support charts and knowledge suited to knowledge packages for growers of specific commodities, are included in Appendix 3.

6.2 Resource and learning investment opportunities

Previous HAL-funded, comprehensive reports have addressed key pathogens and management options, identified gaps and recommended 'best practice' to increase on farm adoption of IPM, and R&D priorities (Anderson, 2010; Donald and Porter, 2010; dal Santo and Holding, 2009; McDougall, 2007, Porter *et al*, 2007b). Their well-stated priorities are not re-stated here, but several excerpts from these reports are included in Appendix 2b and deserve consideration by HAL and the vegetable industry, in addition to those presented independently by this reviewer.

6.2.1 Extension packages

Vegetable growers would benefit from knowledge packages, eg. a risk profile manual similar to that currently available for cereal growers and being developed for processing potato growers. Ideally it would integrate in a user friendly format, knowledge relevant to the risk profile of various planting scenarios - *cultivar x environment x soil type x pathogen/pathogen complex*, with clearly identified critical decision and management influences (see Figure 1). The documents must be dated with the most recent versions readily able to replace old versions, eg. folder insertion and removal.

- ***"Know before you Sow"*** – the critical steps in risk assessment (soilborne pathogen populations, seed quality, planting material suitability and soil type, health etc.) are not readily apparent to all vegetable growers. If these steps were more closely linked to regional and on-farm biosecurity, it is our view the uptake/implementation of them would be strengthened, and growers would in a short time acquire the skills to assess not only risk, but also the relative value of integrated practices over individual disease management options.

  The more comprehensive the integrated knowledge, the more valuable is the risk profile, eg. for farming systems targeting a pathogen with a known inoculum density/disease incidence threshold for the relevant soil type, the risk profile will allow growers to confidently choose or reject the site and/or cultivar before planting - as with the PreDicta B disease risk model for grains (SARDI PreDicta B). Cultivar susceptibility knowledge further increases its value.
- **"*How to*" guides** in hard copy are rare, but appear critical (in the absence of regional extension officers), to increasing adoption of some important practices and technology, in soilborne disease management. Guidelines for risk assessment that detail *how to* assess seed health (available in part as "info leaflets"), detect pathogen (or resistance) problems early, scout/monitor, interpret soil population quantification and thresholds, cultivar and soil type interactions; *how to* determine relative risk associated with crop residue retention

as a carbon source, its timing and the pathogen responses etc. Electronic versions while standard in some industries, are not in the vegetable industry. Their development however is warranted and links to some are provided in Appendix 3, as examples.

Similarly, guidelines on *How to* access web-based information by key words (eg. for AUSVEG, UC IPM, Cornell University IPM websites), would be helpful and simple to prepare.

6.2.2 Demonstration trials and Workshops

Nationally-coordinated but regionally-based, accredited workshops and demonstration trials have proven to be appropriate means of delivery for some information and training (*Fusarium* and *Pythium* workshop notes, 2010). These have the capacity to highlight regional variations of greatest influence on management and pathogens. Workshops and roadshows as delivered through HAL projects (eg. VGO7125, VG06092, VG07110, VG07118) were reportedly successful. The Research to Practice® format, as conducted by the wine grape industry, could be a worthy 'professional development' aim of the vegetable industry. The comprehensive modules have knowledge-building and practical implementation foci, are registered (eg. for subsidised cost contributions) and include opportunity for subsequent skill self-assessment (Research to Practice®).

6.2.3 Human resources and capability building

Vegetable growers in Australia need support to increase their risk assessment and response skills in relation to soilborne disease management. Extension specialists (or industry development officers) are a valuable resource and investment in them in key regional areas is warranted and could be funded via biosecurity funds (and potentially state government contributions). Extension officers have the skills required to engage and motivate vegetable growers, and greatly increase the rate of adoption of key disease and risk management options.

A current example of an effective extension system, established in response to regional pathogen and biosecurity concerns, may be found within the grains industries. Grains Biosecurity Officers (GBOs) are funded through Grains Producers Australia (GPA), through the Emergency Plant Pest Response (EPPR) Levy. Unlike horticultural industries, the grains industries set their EPPR levy above zero and as such they have a 'positive' biosecurity fund that is growing and readily available for incursion response, should it be needed. The funds received over and above the set reserve, are available for other biosecurity activities and it is through these funds and the Grains Farm Biosecurity Program, that GBOs are currently employed (PHA confirmed, pers. comm.).

As is occurring internationally, Australia appears no longer to be training, developing, investing in and retaining discipline specialists within academic and government service institutions. The vegetable industry, like others in horticulture, is aware of the imminent shortage of bacteriologists, mycologists, virologists and nematologists and may wish to engage actively in current discussions on agricultural education, and the potential for a cross-industry funded central horticultural facility for research and diagnostics, and data management, where such specialists could operate and receive cross-industry funding.

6.3 Priority pathogen targets for increased extension effort

The primary pathogen targets of extension efforts should be identified by growers in key production regions. They are likely to be the same as those identified as "key" pathogens in this report. However the improved management of pathogens in complexes (rather than individually) is recommended as a focus, as is the extension of knowledge transferable across soil types and defined disease pressures.

RECOMMENDATIONS

7 PRIORITY RD&E INVESTMENT

The majority of *information* necessary to achieve more reliable control of soilborne vegetable pathogens, is in existence. *Knowledge* gaps however compromise grower capacity to conduct risk assessment by farming systems, and to respond confidently to minimise pathogen impact. Future RD&E must close these gaps and build capacity and practical knowledge that can underpin whole system risk assessment, timely response and effective management decisions. As such, **whole farming systems** should be the research scope of integrated teams, and outcomes of each RD&E activity should provide additional risk factor knowledge and capability to respond to the collective risk, eg. *pathogen* x *cultivar* x *soil type* x *environment*.

For inoculum-dependent pathogens (*Sclerotinia*, *Sclerotium*, *Verticillium* spp. and some Fusaria) knowledge of the influence of soil type and environment on the inoculum density-disease incidence relationship and the economics of inoculum reduction practices, are important.

The R&D program and farming system targets of the integrated APRP1 and 2 research team, and of Hay and Walker's root knot nematode management program (Potatoes Australia, 2011) are good examples of comprehensive approaches to managing a range of pathogens through specific knowledge and capacity building that informs risk assessment and decision-making.

Table 10 : Summary of focus areas for future investment

Focus areas for future investment		
Extension	Development	Research
Packaged, hard copy risk assessment knowledge (dated) - for vegetables susceptible to same/similar pathogen range. (Prior survey of industry could confirm this as the preferred format) Sections*: 5.2.1, 5.2.2, 6.1.1, 6.2.1	Resource and service access guidelines – sources, services available to underpin decision-making. Sections*: 5.1, 5.2.2, Appendix 3	Whole of system and disease complex foci. Integrated teams working on disease complexes, across soil types and disease pressures Sections*: 5.1.1, 5.2.3
How to guides for ready-to-adopt decision and management knowledge Sections*: 6.2.1, Appendix 3	Central horticultural data repository cost-benefit? Sampling economies of scale — for pathogen/chemical resistance, cross resistance, residues Sections*: 5.2, 6.2	Soil inoculum, seed/planting material – quantification of pathogen status – linked to disease and soil community characterisation Sections*: 5.1.3, 5.2.8
Coordinated chemical/pathogen sample submissions - resistance, monitoring and screening. Sections*: 5.2.4	Assisted introduction of farm record software for pathogen management – with manufacturer Sections*: 5.1, 5.2.6, 6.2.3	Quantification tools and rapid molecular screening for more pathogens Sections*: 5.1.3, 5.1.4, 5.2.8, 5.2.10
ICM economics under different disease pressure and soil types x pathogen Sections*: 4.2.2, 5.1.2	Cultivar screening – x soil type x inoculum pressure Sections*:5.2.10, 6.2	Economic thresholds of soilborne inoculum and inoculum reduction strategies in different soil types. Sections*: 5.1.2, 5.2.3
Expertise sharing/training face-to-face. Priority: ready-to-adopt technology; extension officers in key production areas Sections*: 6.2.1 – 6.2.33	Most promising alternatives – x pathogen pressure x soil type, eg. fumigant alternatives, stimulants Sections*: 4.1, 5.1.1, 5.2.3	Chaperonin gene technology – in Australia, soil profiling innovations for microbial community characterisation Sections*: 5.1
Capability building and competency standards for "*Know before you Sow*" concept. Sections*: 6.2.1 – 6.2.3	CTF demonstration of reduced traffic influence on soil structures and specific vegetable pathogen/s Sections*: 5.2.9, Appendix 3	Integrated suppressive soil characterisation - by soil type (and specific pathogen/s and pathogen complexes). Integrate quantification research with subsequent disease, yield and soil community characterisation Sections*: 5.1

Focus areas for future investment		
Extension	Development	Research
	Nursery engagement and increased requirement for seed and transplant data Sections*: 5.2.7	Inoculum reduction innovations - advance melanin and stimulant work; integrate to quantification and community characterisation Sections*: 5.1

* Reference to relevant parts of review text in which this recommendation is described in more detail.

7.1 Priority investment in Extension

Extension is the area that will provide assured returns on investment, undertaking of risk assessment and more reliable pathogen management. Investment in extension at this time, appears more important than applied research. Some development investment is also required.

Extension through the provision of accurate, hard copy, integrated knowledge packages that include decision-making steps on risk factors, and 'ready-to-adopt' practices, is a priority. *How to* Guides in similar form could be incorporated (as for the potato manual under development) or offered as separate documents. Opportunities for self-assessment of acquired competencies are recommended. Extension activities offered in-person, especially by extension/biosecurity officers (as in the grains industries), are likely to have high level of engagement. Industry development officers, consultants, re-sellers are often first contacts for growers and as such must be fully informed.

The priorities and suggested quantum of extension investment is provided below.

Table 11 : Priority investment in extension activities

Extension activity	Recommended Investment in Extension			Industry benefit timeframe
	Priority[x]	Quantum (S)	Timeframe*	
Packaged, hard copy risk assessment knowledge package	1	$200,000 $300,000 – distribution and maintenance	1-year development 1-year distribution and extension activities	1-5 years
How to Guides for ready-to-adopt services, knowledge and practices	1	$100,000	1-year development – release with above	Immediate
In-person training –eg. extension officers, demonstrations etc	1	Shared investment – states? GRDC? Cross-industry? DAFF-biosecurity?	On-going	Immediate
Capability building and competency standards in '*Know before you Sow*' risk assessment	1	Incorporated into above guides. Self-assessment competency tests	On-going	1-5 years
Economics of options -whole system approach - reduction, treatment, rotation etc.	1	$100,000	Expand Villalta[y] across systems, insert into knowledge packages	1-5 years
Sampling and monitoring coordination and guidelines - chemicals, pathogens	2	Started – but need education and co-ordination budget $60,000	Expand - 12 months	Immediate
ICM economics – case studies and competency to interpret risk and RD&E results	2	x cultivar x inoculum pressure x yield/returns $70,000	1 - 2 years	On-going

[x] Ranking1-5:1 = highest priority for investment; * Timeframe for 'ready to adopt' outputs; [y]Villalta and Trapnell, 2010; Villalta *et al*, 2010b

7.2 Priority investment in Development

Investment in inoculum reduction on true seed, seed quality, cultivar breeding and selection, and new chemistry is largely the responsibility of seed and crop protection product manufacturers. The vegetable industries, although reliant on the outputs of such investment, and not necessarily contributors to it, should actively engage in co-ordinated trialling of products under development, in order to identify early any location, soil, inoculum density, or cultivar risks that would ultimately limit their commercial adoption.

Table 12 : Priority investment in development activities

Development activity	Recommended Investment in Development			Industry benefit* timeframe
	Priority	Quantum ($)	Timeframe	
Simplify resource and service access for key decision support and practices - guidelines	1	$120,000	6 months -1 year; on-going maintenance. Commenced: VIDP Knowledge Mgt	Immediate-one year
Central horticultural facility and data repository – feasibility costs/benefits	2	Cross-industry $100,000	1 year	3-5 years
Farm data devices to improve decision-making -– assess for specific purposes and industries. Knowledge gaps filled through development of specific add-ons. Link to education process.	3	Co-investment - with corporates, marketers, DQMAWG/regulators, QA, GPS expertise, HAL assistance	1 year	On-going
Cultivar screening – x soil type x inoculum pressure. National protocol	2 premature for some	$100,000 with seed companies	One year set up; on-going	Annual
Chemistry evaluation – x pathogen pressure x soil type, eg. fumigant alternatives, stimulants.	2	Partnerships - $100,000 with crop protection companies contributing most	One year set-up; on-going	Annual
CTF demonstration and soil management training	3	$50,000 + demonstration site. Co-invest to build on R&D to-date in Tasmania? Queensland? All states?	On-going for 5 years	3-5 years
Enhanced nursery engagement, contribution and reporting	1	Negligible funds. Vegetable industry to take lead - with PHA and HAL support as a recognised as a biosecurity activity	Immediate	Immediate

* Timeframe for 'ready to adopt' outputs

7.2.1 Cross-industry relevance and leveraging potential in extension and development

Recommended investment in development and extension that has cross-industry relevance includes:

- R&D output categorisation system – prepare HAL '*ready-to-adopt*', '*early innovation*' etc symbols to become a recognisable guide to outputs of immediate value. Ready-to-adopt outputs should have priority releases to industry.
- Sampling and monitoring guidelines and harmonised protocols – cross-industry support with diagnostic service providers.
- Central horticultural facility and data repository – cross-industry with state governments, AUSVEG.

- Harmonised chemical protection guidelines and coordinated sampling by region (as for 2,4-D) – state governments, regional councils and research and Development Corporations (RDCs).
- Chemical resistance, cross-resistance screening and economies of scale through coordinated submissions and data management – cross-industry support with DAFF, APVMA (where appropriate).
- Extension/biosecurity officers – shared across key production regions (RDCs, PHA).
- Quantification tools – expand range to more pathogens (seedborne and soilborne); inoculum reduction strategies – cross-industry support, leverage from grains and potatoes.

7.3 Priority investment in Research

Table 13 : Priority investment in research activities

Research activity	Research investment areas		Industry benefit*
	Priority	Timeframe and budget	Timeframe
Farm system focus and integrated team research on disease complexes	1	Short - long term Framework development - $60,000	Establish a transferable (eg to regions, multiple vegetable cropping systems) "farming system research framework" – like potato industries in APRP 1, 2.. Utilise in all relevant projects. 1 year to develop framework
Quantification – multiple pathogens in soil; disease; soil community composition	1	Short-term Technical capabilities $100,000	Increase capabilities for pre-plant detections; requirements for disease predictions and evaluations. Characterise more soil communities as part of R&D on comparative high and low yielding crops. 1 -2 years. Combine with above and below.
Economic thresholds of inoculum and inoculum reduction on seed and in soil	1	On-going Expand evaluations in all management strategy R&D $15,000 to all projects	Clearly identify inoculum-dependent and independent diseases. Increase economic knowledge associated with relevant strategies over >1 season or rotation cycle. 2-5 years, on-going. Combine with above in each relevant R&D project.
Economics of innovative inoculum reduction - eg. melanin, natural stimulants	2	Short-term $100,000	Determine economic reduction potential – as a guide for R&D decisions on innovative sclerotia reduction – < 5-years
Advance in Australia chaperonin gene, soil profiling innovations	3	Long-term Unknown costs – commence with study scholarship?	Link with APRP 2. - 5+ years International training in this is likely to be the most economically-viable first-step.
Suppressive soil characterisation for pathogens *in complex*	2	Long-term Unknown costs – commence with study scholarship?	Link with above. 5-10 years International training in this is likely to be the most economically-viable first-step.

* Timeframe for 'ready to adopt' outputs

7.3.1 Cross-industry relevance and leveraging potential in research

- Selective soil enrichment and introduced microbial fate patterns – with grains, potato industries; New Zealand, Canada (chaperonin gene work Lazarovits, 2011)
- Microbial community manipulation and delivery technology – seed multi-nationals (seed treatment and infusion techniques?); grains industries, veterinary multi-nationals (esp. those investigating BCAs, eg. hypovirulence, mycotoxins (i.e. as in corn), atoxigenic *Aspergillus* spp. (as in California)
- Quantification, profiling tools and applications – leveraged from potatoes and grains and service providers (eg. SARDI). New innovations through national (and international, eg. New Zealand, Canada, UK) grains, medical and veterinary research programs.

REFERENCES

Anderson, A. 2010. Root Vegetables Think Tank. HAL Project VG09078.

Badgery-Parker, J. 2009. Keep It Clean. NSW Dept Primary Industries. 147 pp.

Conde, B., M. Traynor, L. Tran-Nguyen, B. Sithell, B. 2010. Grafting and *Fusarium* wilt of snake bean. *In* Donald and Porter, 2010.

Controlled traffic farming (CTF) adoption guidelines for the vegetable industry. (Undated) http://www.tia.tas.edu.au/__data/assets/pdf_file/0007/240199/Controlled-Traffic-Farming-Adoption-Guidelines.pdf

Cornell Crop Management (and other land grant university extension services): http://www.nysaes.cals.cornell.edu/recommends/

Cornell University. State Integrated Pest Management Program: www.nysipm.cornell.edu

Cornell University Production Guides for NYS IPM. 2012. NYS Dept Agric & Markets. Publications: No 135 Cucumbers – squash; No 138 Potatoes.

dal Santo, P. and R. Holding. 2009. Best Practice for Vegetables. Good Agricultural Practices (GAP). HAL Report and factsheets VG07109.

dal Santo, P. and R. Holding. 2009b. Best Practice – Fusarium, Pythium and Rhizoctonia Root Rots in Vegetables. 20pp. (component of HAL VG07109).

dal Santo, P. and R. Holding. 2009c. Best Practices – Sclerotinia in Green Beans. 21pp. (component of HAL VG07109).

dal Santo, P. and R. Holding. 2009d. Best Practices – Sclerotinia in Lettuce. 22pp. (component of HAL VG07109).

Davis, R.M., J.J. Hao, and M.K. Romberg. 2007. Efficacy of germination stimulants of sclerotia of *Sclerotium cepivorum* for management of white rot of garlic. Plant Dis. 91:204-208.

Donald, C. and I. Porter. 2010. Best Practice IPM Strategies for Control of Major Soilborne Diseases of Vegetable Crops throughout Australia. *Project 2.2*. HAL Final report VG07125.

Donald, C., C. Horlock, B. Conde, O. Villata and I. Porter. 2010. Towards Sustainable Integrated Control of Soilborne Plant Diseases – A review of available and emerging chemical and non-chemical strategies and their potential compatibility with IPM programs. *In* Donald and Porter, 2010.

Edwards, J. 2011. Identifying microbial committees in disease suppressive soils as a means of improving root health of potatoes. HAL Report Project PT07038.

Grain Growers Limited. 2012. Technology survey. http://www.graingrowers.com.au/images/Growers_Talk_Technology_130812.pdf

Greenhill, A., K. Plummer, I. Porter. 2010. Disruption of Fungal Resting Structures. *In* Donald, C. and I. Porter. 2010.

Hailstones, D. 2011. Identification and Monitoring of Resistance in Vegetable Crops in Australia. HAL Final Report VG07119.

Hall, B., L. Tesoriero and L. Forsyth. 2011. Identification and Monitoring of Resistance in Vegetable Crops in Australia. *In* Hailstones, 2011.

Hao, J.J., M.E. Yang, and R.M. Davis. 2009. Effect of Soil Inoculum Density of *Fusarium oxysporum* f. sp. *vasinfectum* Race 4 on Disease Development in cotton. Plant Dis. 93:1324-1328.

Keen, B. and T. Vancov. 2010. *Phytophthora cinnamomi* suppressive soils. *In* Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology. A. Mendez-Vilas (Ed) pp239-247.

Kirkwood, I., K. Ophel-Keller, T. Slater. N. Crump, L. Sparrow, C. Wilson, G. Lazarovits and R. Falloon. 2009. Australian Potato Research Program 1 2004-2009. Final Report Project PT04016.

Koike,S., P. Gladders and A. Paulus. 2006. Vegetable Diseases: A Color Handbook (USA)

Koike, ST., K.V. Subbarao, RM Davis and TA Turini. 2003. Vegetable Diseases caused by Soilborne Pathogens. UC ANR Publication 8099 13pp. Also available on-line: http://anrcatalog.ucdavis.edu/pdf/8099.pdf

Lamers, J.G., W.T. Runia, L.P.G. Molendijk, and P.O. Bleekee, 2010. Perspectives of Anaerobic Soil Disinfestation. Acta Hort. (ISHS) 883:277-283; *Online*: Acta Hort. 883. VII International Symposium on Chemical and Non-chemical Soil and Substrate Disinfestation. http://www.actahort.org/books/883/883_34.htm

Lazarovits. G. 2011. Identifying microbial communities in diseases suppressive soils as a means of improving root health of potatoes. *In* Edwards, 2011.

Mann, R. and S. Mattner. 2010. Fungal Derived Volatiles. *In* Donald, C. and I. Porter. 2010.

Mattiazzi, C. 2012. iPhone app speeds macadamia data transfer. Pp16-17 Australian Nutgrower 26 (3): 16-17.

McDougall, S. 2007. Benchmarking Vegetable Integrated Pest Management Systems Against Other Agricultural Industries or 'Field Vegetable IPM Stocktake'. NSWDPI and HAL Final Report VG05043.

McDougall S. and L. Orr, H. 2011. Business case: IPM in lettuce. InnoVeg and HAL (component of National Vegetable IPM Co-ordination project-VG09191).

Monsanto. Integrated Farming Systems. http://www.monsanto.com/products/Pages/integrated-farming-systems.aspx

Noble, R. 2011. Risks and Benefits of soil amendment with composts in relation to plant pathogens. Austral. Plant Pathol. 40:157-167.

Persley, D., T. Cooke and S. House. 2010. Diseases of vegetable crops in Australia. CSIRO Publishing and Queensland Government. pp292.

Porter, I., R. Brett and S. Mattner, 2007a. Managmenet of soil health for sustainable vegetable production. HAL Final Report Project VG06090.

Porter, I., C. Donald, and E. Minchinton. 2007b. National Vegetable Industry IPM Pathology GAP Analysis. HAL Final Report VG06092.

Potatoes Australia. Oct/Nov 2011. DNA tests identify different species of root knot nematode pp11-12.

Pung, H. and S. Cross. 2010. Development of strategies for managing Sclerotinia diseases in green beans and lettuces in Tasmania. *In* Villalta and Porter, 2010.

Pung, H. and S. Cross. 2004. Developing Alternative Methods for Sclerotinia disease control on vegetables in Tasmania. HAL Final Report VG00048.

Pung, H., S. Cross, K Ophel-Keller and A. McKay. 2007. Investigations on *Rhizoctonia solani* in cropping soils and vegetable crops. Project HVG05090 report on-line: http://www.peracto.com.au/publications/rhizoctonia-article-Aug07.pdf.

Pythium and Fusarium Workshop. 2010. Notes from Sydney Botanic Gardens Workshop (component of Donald, C. and I. Porter. 2010) 16pp.

Research to Practice® - http://www.awri.com.au/industry_support/courses-seminars-workshops/research-to-practice/

SARDI PreDicta B http://www.sardi.sa.gov.au/pestsdiseases/diagnostic_service/predicta_b

Scholefield Robinson and EconSearch. 2002. Rootstock Analysis Planting Tool. GWRDC Project.

Scoble, C., I. Porter, O. Villata, D. Wite, D, Riches, and K. Plummer. 2010. Plant Derived Compounds. *In* Donald, C. and I. Porter. 2010.

Scott, J.C., T. Gordon, S.C. Kirkpatrick, S.T. Koike, M.E. Matheron, O.E. Ochoa, M.J. Truco, and R.W. Michelmore. 2012. Crop Rotation and Genetic Resistance Reduce Risk of Damage from Fusarium Wilt in Lettuce. California Agric 66(1):20-24.

Stirling, G. 2012. Managing the Nematode Threat. HAL Report MT09067.

Syngenta. 2011. http://www.syngenta.com/global/corporate/en/products-and-innovation/product-brands/seed-care/Pages/vibrance.aspx

Tegg, R., L. White, P. Beveridge, C. Wilson, K Ophel-Keller and I. Kirkwood. *Undated* (2010). Seed tuber-borne inoculum. Australian Potato Research Project Phase 2 (Presentation)

Tesoriero, L., L. Forsyth, D. Riches, and C. Donald. 2010. IPM Strategies for soilless vegetable production systems. *In* Donald, C. and I. Porter. 2010.

Tullberg J.N., D.F. Yule and D. McGarry. 2007. Controlled traffic farming – from research to adoption in Australia. Soil & Tillage Research 97:272-281 and online at: www.sciencedirect.com

UC IPM website: http://www.ipm.ucdavis.edu/

VicDPI Factsheet. 2010. Managing Soilborne Diseases in Vegetables – rotation with green manure and biofumigant crops. (component of Villalta and Porter, 2010).

VicDPI Factsheet. 2010. VicDPI. 2011. Managing Sclerotinia Diseases in Vegetables. (component of Villalta and Porter, 2010).

VicDPI Factsheet. 2010. Improving Soil Health for Yield and Profit in Vegetables – soil health management shows economic and environmental benefits (component of Project VG07008)

Villalta, O. and I. Porter. 2010. Integrated Management of Soilborne Pathogens (Sclerotinia). *Project 2.1*. (8 chapters) Final Report HAL VG07126.

Villalta,O. and L. Trapnell. 2010. Economic analysis of new strategies evaluated for managing Sclerotinia and other soilborne diseases in vegetables. *In* Villalta and Porter, 2010.

Villalta, O., D. Wite, R. Holding and I Porter. 2010a. Evaluating fungicide and alternative treatments for Sclerotinia control in lettuce and green beans. *In* Villalta and Porter, 2010.

Villalta, O., C. Donald, C. Scoble, D. Riches, D. Wite, S. Mattner, I Porter and H. Pung. 2010b. Economic analysis of new strategies evaluated for managing Sclerotinia and other soilborne diseases in vegetables. *In* Villalta and Porter, 2010.

Villalta, O., C. Donald, C. Scoble, D. Wite, D. Riches, S. Mattner, R. Jones, G. Rose, D. Allen and I. Porter. 2010c. Influence of rotation and biofumigation on soilborne diseases, yield, and soil in vegetable production in Victoria. *In* Donald and Porter, 2010.

APPENDIX 1A

Past Project focus areas

Hosts / R&D focus	Alliums	Asian Veg	Brassica	Cucurbits	Leafy	Legumes	Root crops	Solana-ceous	Other
Diagnosis and detection			3		2	1	1	1	
Key disease information				1		1		1	1
Sampling; decision-making strategies					2	3			2
Seedling health			2		3	1	1		2
Cultural management		1	4	3	5	4	2	1	4
Biological control				1	3		1	1	
Chemical control			2	2	5	3	3	2	1
Other non-chemical tools	1		6		2	3	1	3	1
Complete mgt guidelines			3		5	2	1	2	2
Resources			3		1		1	2	
TOTAL Research Projects	1	1	11	5	12	9	7	8	7

Source: Porter *et al*, 2007

APPENDIX 1B

Documents reviewed – Australian soilborne vegetable disease management

Anderson, A. 2010. Root Vegetables Think Tank. HAL Project VG09078.

Badgery-Parker, J. 2009. Keep It Clean. NSW Dept Primary Industries. 147 pp.

Conde, B., M. Traynor, L. Tran-Nguyen, B. Sithell, B. 2010. Grafting and *Fusarium* wilt of snake bean. *In* Donald and Porter, 2010.

Controlled traffic farming (CTF) adoption guidelines for the vegetable industry. (Undated) http://www.tia.tas.edu.au/__data/assets/pdf_file/0007/240199/Controlled-Traffic-Farming-Adoption-Guidelines.pdf

dal Santo, P. and R. Holding. 2009. Best Practice for Vegetables. Good Agricultural Practices (GAP). HAL Report and factsheets VG07109.

dal Santo, P. and R. Holding. 2009b. Best Practice – Fusarium, Pythium and Rhizoctonia Root Rots in Vegetables. 20pp. (component of HAL VG07109).

dal Santo, P. and R. Holding. 2009c. Best Practices – Sclerotinia in Green Beans. 21pp. (component of HAL VG07109).

dal Santo, P. and R. Holding. 2009d. Best Practices – Sclerotinia in Lettuce. 22pp. (component of HAL VG07109).

Donald, C. and I. Porter. 2010. Best Practice IPM Strategies for Control of Major Soilborne Diseases of Vegetable Crops throughout Australia. *Project 2.2*. HAL Final report VG07125.

Donald, C., C. Horlock, B. Conde, O. Villata and I. Porter. 2010. Towards Sustainable Integrated Control of Soilborne Plant Diseases – A review of available and emerging chemical an dnon-chemical strategies and their potential compatibility with IPM programs. *In* Donald and Porter, 2010.

Edwards, J. 2011. Identifying microbial committees in disease suppressive soils as a means of improving root health of potatoes. HAL Report Project PT07038.

Grain Growers Limited. 2012. Technology survey. http://www.graingrowers.com.au/images/Growers_Talk_Technology_130812.pdf

Greenhill, A., K. Plummer, I. Porter. 2010. Disruption of Fungal Resting Structures. *In* Donald, C. and I. Porter. 2010.

Hailstones, D. 2011. Identification and Monitoring of Resistance in Vegetable Crops in Australia. HAL Final Report VG07119.

Hall, B., L. Tesoriero and L. Forsyth. 2011. Identification and Monitoring of Resistance in Vegetable Crops in Australia. *In* Hailstones, 2011.

Kirkwood, I., K. Ophel-Keller, T. Slater. N. Crump, L. Sparrow, C. Wilson, G. Lazarovits and R. Falloon. 2009. Australian Potato Research Program 1 2004-2009. Final Report Project PT04016.

Mann, R. and S. Mattner. 2010. Fungal Derived Volatiles. *In* Donald, C. and I. Porter. 2010.

Mattiazzi, C. 2012. iPhone app speeds macadamia data transfer. Pp16-17 Australian Nutgrower **26 (3)**: 16-17.

McDougall, S. 2007. Benchmarking Vegetable Integrated Pest Management Systems Against Other Agricultural Industries <u>or</u> 'Field Vegetable IPM Stocktake'. NSWDPI and HAL Final Report VG05043.

McDougall S. and L. Orr, H. 2011. Business case: IPM in lettuce. InnoVeg and HAL (component of National Vegetable IPM Co-ordination project-VG09191).

Noble, R. 2011. Risks and Benefits of soil amendment with composts in relation to plant pathogens. Austral. Plant Pathol. **40**:157-167.

Persley, D., T. Cooke and S. House. 2010. Diseases of vegetable crops in Australia. CSIRO Publishing and Queensland Government. pp292.

Porter, I., R. Brett and S. Mattner, 2007a. Managmenet of soil health for sustainable vegetable production. HAL Final Report Project VG06090.

Porter, I., C. Donald, and E. Minchinton. 2007b. National Vegetable Industry IPM Pathology GAP Analysis. HAL Final Report VG06092.

Potatoes Australia. Oct/Nov 2011. DNA tests identify different species of root knot nematode pp11-12.

Pung, H. and S. Cross. 2010. Development of strategies for managing Sclerotinia diseases in green beans and lettuces in Tasmania. *In* Villalta and Porter, 2010.

Pung, H. and S. Cross. 2004. Developing Alternative Methods for Sclerotinia disease control on vegetables in Tasmania. HAL Final Report VG00048.

Pung, H., S. Cross, K Ophel-Keller and A. McKay. 2007. Investigations on *Rhizoctonia solani* in cropping soils and vegetable crops. Project HVG05090 report on-line: http://www.peracto.com.au/publications/rhizoctonia-article-Aug07.pdf.

Pythium and Fusarium Workshop. 2010. Notes from Sydney Botanic Gardens Workshop (component of Donald, C. and I. Porter. 2010) 16pp.

Research to Practice® - http://www.awri.com.au/industry_support/courses-seminars-workshops/research-to-practice/

SARDI PreDicta B http://www.sardi.sa.gov.au/pestsdiseases/diagnostic_service/predicta_b

Scholefield Robinson and EconSearch. 2002. Rootstock Analysis Planting Tool. GWRDC Project.

Scoble, C., I. Porter, O. Villata, D. Wite, D, Riches, and K. Plummer. 2010. Plant Derived Compounds. *In* Donald, C. and I. Porter. 2010.

Stirling, G. 2012. Managing the Nematode Threat. HAL Report MT09067.

Tegg, R., L. White, P. Beveridge, C. Wilson, K Ophel-Keller and I. Kirkwood. *Undated* (2010). Seed tuber-borne inoculum. Australian Potato Research Project Phase 2 (Presentation)

Tesoriero, L., L. Forsyth, D. Riches, and C. Donald. 2010. IPM Strategies for soilless vegetable production systems. *In* Donald, C. and I. Porter. 2010.

Tullberg J.N., D.F. Yule and D. McGarry. 2007. Controlled traffic farming – from research to adoption in Australia. Soil & Tillage Research **97**:272-281 and online at: www.sciencedirect.com

VicDPI Factsheet. 2010. Managing Soilborne Diseases in Vegetables – rotation with green manure and biofumigant crops. (component of Villalta and Porter, 2010).

VicDPI Factsheet. 2010. VicDPI. 2011. Managing Sclerotinia Diseases in Vegetables. (component of Villalta and Porter, 2010).

VicDPI Factsheet. 2010. Improving Soil Health for Yield and Profit in Vegetables - soil health management shows economic and environmental benefits (component of Project VG07008)

Villalta, O. and I. Porter. 2010. Integrated Management of Soilborne Pathogens (Sclerotinia). *Project 2.1*. (8 chapters) Final Report HAL VG07126.

Villalta,O. and L. Trapnell. 2010. Economic analysis of new strategies evaluated for managing Sclerotinia and other soilborne diseases in vegetables. *In* Villalta and Porter, 2010.

Villalta, O., D. Wite, R. Holding and I Porter. 2010a. Evaluating fungicide and alternative treatments for Sclerotinia control in lettuce and green beans. *In* Villalta and Porter, 2010.

Villalta, O., C. Donald, C. Scoble, D. Riches, D. Wite, S. Mattner, I Porter and H. Pung. 2010b. Economic analysis of new strategies evaluated for managing Sclerotinia and other soilborne diseases in vegetables. *In* Villalta and Porter, 2010.

Villalta, O., C. Donald, C. Scoble, D. Wite, D. Riches, S. Mattner, R. Jones, G. Rose, D. Allen and I. Porter. 2010c. Influence of rotation and biofumigation on soilborne diseases, yield, and soil in vegetable production in Victoria. *In* Donald and Porter, 2010.

Documents reviewed - international soilborne vegetable disease management

Cornell Crop Management (and other land grant university extension services): http://www.nysaes.cals.cornell.edu/recommends/

Cornell University. State Integrated Pest Management Program: www.nysipm.cornell.edu

Cornell University Production Guides for NYS IPM. 2012. NYS Dept Agric & Markets. Publications: No 135 Cucumbers – squash; No 138 Potatoes.

Davis, R.M., J.J. Hao, and M.K. Romberg. 2007. Efficacy of germination stimulants of sclerotia of *Sclerotium cepivorum* for management of white rot of garlic. Plant Dis. **91**:204-208.

Hao, J.J., M.E. Yang, and R.M. Davis. 2009. Effect of Soil Inoculum Density of *Fusarium oxysporum* f. sp. *vasinfectum* Race 4 on Disease Development in cotton. Plant Dis. **93**:1324-1328.

Keen, B. and T. Vancov. 2010. *Phytophthora cinnamomi* suppressive soils. *In* Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology. A. Mendez-Vilas (Ed) pp239-247.

Koike,S., P. Gladders and A. Paulus. 2006. Vegetable Diseases: A Color Handbook (USA)

Koike, ST., K.V. Subbarao, RM Davis and TA Turini. 2003. Vegetable Diseases caused by Soilborne Pathogens. UC ANR Publication 8099 13pp. Also available on-line: http://anrcatalog.ucdavis.edu/pdf/8099.pdf

Lamers, J.G., W.T. Runia, L.P.G. Molendijk, and P.O. Bleekee, 2010. Perspectives of Anaerobic Soil Disinfestation. Acta Hort. (ISHS) 883:277-283; *Online*: Acta Hort. 883. VII International Symposium on Chemical and Non-chemical Soil and Substrate Disinfestation. http://www.actahort.org/books/883/883_34.htm

Lazarovits. G. 2011. Identifying microbial communities in diseases suppressive soils as a means of improving root health of potatoes. *In* Edwards, 2011.

Monsanto. Integrated Farming Systems. http://www.monsanto.com/products/Pages/integrated-farming-systems.aspx

Scott, J.C., T. Gordon, S.C. Kirkpatrick, S.T. Koike, M.E. Matheron, O.E. Ochoa, M.J. Truco, and R.W. Michelmore. 2012. Crop Rotation and Genetic Resistance Reduce Risk of Damage from *Fusarium* Wilt in Lettuce. California Agric **66(1)**:20-24.

Syngenta. 2011. http://www.syngenta.com/global/corporate/en/products-and-innovation/product-brands/seed-care/Pages/vibrance.aspx

UC IPM website: http://www.ipm.ucdavis.edu/

APPENDIX 2A

Excerpts from past reports on pathogen importance, information gaps and management options

Key soilborne pathogens and the diseases they cause in Australian vegetable production systems

Pathogen	Crop	Disease
Sclerotinia		
Sclerotinia minor	Lettuce	Lettuce drop
Sclerotinia sclerotiorum	Beans	White mould
	Brassicas	White mould or soft rot
	Potatoes	White mould or Sclerotinia rot
	Lettuce	Lettuce drop
	Cucumber	Stem and fruit rot
	Tomato	Stem and fruit rot
	Artichoke	Basal stem rot
	Carrots	Sclerotinia rot, crown rot
Pythium		
P. ultimum P. sylvaticum. P. dissotocum or *P. violae*	Lettuce seedlings	Damping off
P. ultimum, P. aphanidermatum, P. irregulare, P. myriotylum, P. spinosum, P. mamillatum	Cucumber seedlings	Damping off
P. myriotylum or *P. aphanidermatum*	Capsicum	Sudden wilt
P. sulcatum or *P. violae*	Carrots	Cavity spot
P. dissotocum, P. coloratum	Lettuce	Root rot
P. ultimum, P. aphanidermatum, P. myriotylum, P. spinosum	Cucumber	Root rot & sudden wilt
P. dissotocum (and others)	Beans	Root rot
Fusarium		
Fusarium spp.	Vegetable seedlings	Damping off
F. oxysporum f.sp. *pisi* (races 1 & 6)	Snow Pea	Fusarium wilt (true wilt & near wilt)
		Fusarium wilt & crown rot
F. oxysporum f. sp. *basilica*	Sweet and Thai basil	Fusarium wilt
F. oxysporum f. sp. *cucumerinum* (Foc), or possibly (and less frequently) *F. oxysporum* f. sp. *radicis-cucumerinum*	Cucumber	
F. oxysporum f.sp. *tracheiphilum*	Snake bean	Fusarium wilt
F. oxysporum f. sp. *lycopersici*	Tomatoes	Fusarium wilt & root rot
F. oxysporum, Fusarium avenaceum	Leeks	Fusarium foot rot
F. verticillioides, F. proliferatum, F. subglutinans	Sweet corn	Fusarium cob rot
Fusarium spp.	Beans	Fusarium wilt & root rot
	Carrots	Crown rot
	Parsley	
	Celery	
Rhizoctonia		
Rhizoctonia solani		
AGs 1, 2.1*, 2.2, 3, 4, 10, 11	Beans	Brown root rot
AGs 2.1*, 2.2, 4, 9	Brassicas	Stem canker
AGs 2.1, 2.2, 3*	Potatoes	Black scurf (tubers), stem canker, wilt (occasionally), tuber canker (occasionally)
AGs 2.1, 8	Onions	Onion Mallee stunt
AGs 1, 4	Lettuce	Bottom rot
AGs 1	Carrot	Carrot black, crown rot
R. crocorum	Carrot	Violet root rot
Rhizoctonia spp.	Cucumber seedlings	Root rot & collar rot

* denotes predominant pathogenic AG

Source: Donald, *et al*, 2010 (Table 1.1) in Donald and Porter, 2010.

'Best practice" IPM strategies for key soilborne pathogens in Australia. Research priorities fitted against project modules.

Sclerotinia

Eradication of pathogen survival structures	Disruption of the infection process	Strengthening of the host crop against disease	Exploiting host resistance to control disease
*Fungicide use (reduce spray number and improve application methods for existing chemicals, evaluate products in IR4 program, consider fluazinam +/- wetter) Develop fungicide resistance management guidelines (will require increase in the number of registered products) *Fumigant DMDS for severe infestations *Direct treatment of sclerotia on crop residues (eg. application of biologicals *S. sclerotivorum* or *C. minitans* , limes or fungicides immediately after harvest) Volatiles including (biofumigants) from organic matter , crucifer derived ITCs, DMDS, and DADS	#Disrupting and silencing key pathogenicity factors (eg Gene silencing of melanin pathway enzyme and disruption of the pathway for melanin production) Soil surface modification (as barriers to infection of leaves and inhibition of apothecial production eg. lime, Perlka, films, biological, physical, mulches etc) Transmissible hypovirulent strains of *S. minor* Inhibition of apothecia of *S. sclerotiorum* with chemicals/herbicides	Salicylic acid systemic acquired resistance (including induction by analogues INA and BTH) *Silicon mediated systemic acquired resistance Minimising crop conditions that favour disease (*S. sclerotiorum*) eg. row orientation, irrigation manipulation, fertiliser, shortening flowering period Use of biological controls eg. Contans™ as a foliar spray on bean flowers Manipulation of plant surfaces to produce sub-optimal conditions for infection. (eg. relationship between petal/plant pH and susceptibility of bean varieties to infection, increasing pH in fungicide mixes to above pH 7 for foliar applications	Screen plants for resistance, including overseas lines Selection of bean varieties for short flowering periods and less dense canopies Consider the use of GM mechanisms and crops Antifungal proteinases Oxalate oxidases

Best Practice IPM strategies for the control of soilborne diseases in vegetable crops

Source: Donald, *et al*, 2010 (1.20 Appendix 1.2) in Donald and Porter, 2010.

Control strategies used to manage key soilborne pathogens in Australia

Pathogen	Crop	Predominant control strategy	Other known controls
Sclerotinia minor	Lettuce	Seedling drench – Filan® (boscalid) or Rovral® (iprodione) (mainly Filan®) at transplanting Spray application (low volume) Filan® or Rovral® irrigated in (3 wks after planting) Up to 3 or 4 applications mainly of Filan® only per crop Crop rotation (limited)	Varietal selection (fancy lettuce less susceptible than Cos lettuce) Hydroponics Fumigation (mainly metham sodium) Controlled traffic fixed bed to reduce compaction Oats/green manure break crops Biofumigant crops Wider planting – canopy control Biocontrol – results not good Avoid excessive vigour – smaller heads, less disease. Deep burial (mainly used overseas)
Sclerotinia sclerotiorum	Beans	Two to three sprays with Filan® (boscalid) during flowering Rotation, however, some rotation crops also susceptible (lettuce, potatoes etc)	Calcium sprays (foliar) Irrigation, moisture control, manipulation of fertiliser input around flowering Cereal and pasture break crops Variety selection (less dense) Flowering period (short vs long) – eg. quick petal drop Micro-gypsum sprays
Pythium spp.	Various	Fumigation (metam sodium, capsicum seedling diseases only, carrot, parsnip) Fungicides (metalaxyl - parsley, parsnip, carrot; metalaxyl, phos acid, Aliette® (fosetyl), Previcur® (propamocarb), Terrazole® (etridiazole) – cucumbers but not registered for greenhouse uses) Host resistance (or tolerance) (lettuce, parsley, parsnip, carrot) Climate management (eg. irrigation management for parsley or parsnip or soil temperature management by changing colour of plastic from black to white to reduce soil temperature for capsicum). Rotation (greenhouse cucumber) Hygiene (greenhouse cucumber) Compost/mulch (greenhouse cucumber) Controlling fungal gnats (green house cucumber) Grafting (cucumbers and melons)	Oxygenation of hydroponic solutions. Nutrient and temperature management (hydro lettuce). Biocontrol (hydro lettuce).
Fusarium spp.	Various	Fumigation (mainly Telone® or metam sodium, greenhouse crops, field tomatoes and rockmelon) Fungicide seed dressing (mainly Thiram, peas, beans, snow peas(in trials only)) Moving to new land (snow peas) Grafting (cucumbers, snake beans, tomatoes, melons) Host resistance (or tolerance) (cucumber) Water source treatment (greenhouse crops) Rotation (cucumbers, tomatoes) Hygiene (cucumbers, tomatoes) Delayed sowing (near wilt of snow peas)	Removal of leaves and/or infected plants (cucumber)
Rhizoctonia spp.	Potato*	Seed management potatoes eg. certification, UV treatment for increased vigour, sprouting, chemical treatment including Maxim® (fludioxonil), Monceren® (Pencycuron) In field chemical treatment potatoes eg. Amistar® (azoxystrobin), PCNB, Rovral® (iprodione), Rhizolex® (tolclofos-methyl) Paddock preparation and selection (weed management, diagnostics, thresholds) Crop rotation	Soil health and management of soilborne inoculum (cultural controls, composts, nutrients, tillage) Crop management (planting depth, temperature, nutrition, minimising wounding) Minimising crop stress (eg. reducing windblasting) Cultivar resistance

* Rhizoctonia spp.cause disease in many vegetable crops but predominant control strategies relate to potato. Few controls in place for other crops.

Source: Donald, *et al*, 2010 (Table 1.2) in Donald and Porter, 2010.

IPM compatible non-chemical control options for management of key soilborne pathogens of vegetable crops

Table 1.3 IPM compatible non-chemical control options for management of key soilborne pathogens of vegetable crops.

	Crop Rotation	Rouging	pH	Nutrition	Composts	Resistance and grafting	Surfactants and bio-surfactants	Plant volatiles	Biocontrol	Hypovirulence	SAR	ISR
Pythium			*P. sulcatum* (cavity spot) increase to 7.2	Increase Ca (cucumber and carrot) Increase Si (cucurbits, early application)			Particularly for zoosporic Pythium and hydroponic situations		Seed treatments of *P. oligandrum*	Non-transmissible hypovirulent strains eg. *P. oligandrum, P. nunn, P. mycoparasiticum, P. periplocum*	Chitin	*Pseudom nas* spp. eg. *P. aphanide matum* of cucumbe
Fusarium			*F. oxysporum* (cucurbits) increase to 6.5-7	N as NO_3^- rather than NH_4 Increase K (wilts) Increase B Increase Si (cucurbits)		Grafting - Cucurbits and snake bean (anything with low density plantings) where conidia of Fusarium not airborne Partially resistant basil available. Resistance in pea		Pepper/mustard, clove or cassia Crucifer derived ITCs		Non-transmissible hypovirulent strains of *F. oxysporum*	SA induced SAR Chitin BTH, BABA induced SAR	*P. fluoresce e* against Fusarium wilt *Serratia marcesce s* against Fusarium wilt
Sclerotinia	Broccoli as preceeding crop Biofumigant break crops	Of lettuce crops to prevent inoculum build up				Selection of bean varieties for low canopy density, upright stature		Oregano Fennel Crucifer derived ITCs	*Sporidesmium sclerotivorum*, low dose after harvest before discing. *C. minitans* immediately after harvest	Transmissible hypovirulent strains of *S. minor* and *S. homeocarpa*, NOT *S. sclerotiorum* as it has many vegetative compatibility groups	SA induced SAR INA, BTH induced SAR	
Rhizoctonia				N as NO_3^- rather than NH_4 Increase P Increase S Increase B						Non transmissible hypovirulent strains of *R. solani* and *P. oligandrum*	SA induced SAR Chitin	
General	Rotation/integrated cropping systems/reduced tillage for soil health, biological activity				Addition to nursery mixes to suppress damping off diseases				At harvest applications of some BCAs to enable pathogen to increase on organic matter and parasitise propagules on crop (eg. *Trichoderma* and P. nunn)		SAR	

Source: Donald, *et al*, 2010 (Table 1.3) in Donald and Porter, 2010.

APPENDIX 2B

USA registered Biological Control Agents (BCAs)

Registered biological control agents with approval for use in organic production of many vegetable and cucurbit crops in various US states.

Biological control agent	Trade name/s	Pathogen target
Streptomyces lydicus WYEC 108	Actinovate AG, Actino-iron	*R. solani, Pythium* spp., *Fusarium* spp., *Sclerotinia* spp.
Streptomyces griseoviridis	Mycostop Mix, Mycostop Biofungicide	*R. solani, Pythium* spp., *Fusarium* spp.
Conioththyrium minitans	Contans WG*	*Sclerotinia* spp.
Trichoderma harzianum str T-22	PlantShield HC; T-22 HC	*R. solani, Pythium* spp., *Fusarium* spp.
Trichoderma harzianum, KRL-AG2	RootShield granule; RootShield WP	'damping off' by *R. solani* and *Pythium* spp.
Gliocladium catenulatum	Prestop Biofungicide WP	*R. solani, Pythium* spp., *Fusarium* spp.
Bacillus subtilis str. QST713	Serenade Soil	*R. solani, Pythium* spp., *Fusarium* spp.
Bacillus subtilis	Taegro Biofungicide	*R. solani*, *Fusarium* spp.

Source: Cornell University Production Guides for NYS IPM. 2012. NYS Dept Agric & Markets. Publication No 135 Cucumbers and Squash.

* has demonstrated efficacy in NYS organic cucurbit farming systems.

APPENDIX 3A

Examples of decision support and integrated knowledge suited to grower knowledge packages and "how to" guides

Disease	Cucumber	Musk melon	Pumpkin	Summer squash	Winter squash	Water melon
Bacterial wilt	H, R	M	M,V	M	L	-
Powdery mildew	M, R	M, R	H, R	H, R	M, R	M
Black rot (gummy stem blight)	L	M	M	L	M	M
Fusarium wilt	-	H, R	-	-	-	-
Fusarium crown rot	L	L	H	M	M	L
Phytophthora blight	H	L	H	H	H	H
Angular leaf spot	L, R	L	M	L	M	L
Downy mildew	M, R	M, R	H	M	H	L
Viruses	L, R	H	M	H, R	M	L

R=resistant varieties exist; L=low (occurs, but rarely in damaging levels); M=moderate; H=high level of susceptibility to pest; V=variable susceptibility among varieties; - = pest tolerance for a particular crop is unknown.

Source: *Resource Guide for Organic Insect and Disease Management. Crop Management Practices – Cucurbits.* http://web.pppmb.cals.cornell.edu/resourceguide/cmp/cucurbit.php. (Adapted from the Cornell Pest Management Guidelines for Vegetables).

Potential Interactions of Crops Grown in Rotation with Cucurbits (USA)

Crops in Rotation	Potential Rotation Effects	Comments
Many crops	*Decrease* weeds	**Mulched** vine crops help reduce weed populations for subsequent crops. Mulched cucurbits are a good choice prior to growing crops where weed control is challenging.
Carrot, lettuce, spinach and other direct seeded crops.	*Increase* weeds in direct seeded crops	**Unmulched** vine crops are often very weedy. Do not follow with direct seeded crops such as carrot, parsnip, lettuce, or spinach.
Eggplant, pepper	*Increase Phytophthora capsici*	*Phytophthora capsici* causes collar rot of eggplant and Phytophthora blight in cucurbits and peppers. Use a rotation of more than 3 years between these crops. Also found on weeds: common purslane, eastern black nightshade, horsenettle, velvetleaf, field pepperweed, field pennycress, Virginia pepperweed.
Broccoli, cauliflower, Brussels sprouts, kale, cabbage, collards, radish, rutabaga, turnip, daikon	*Decrease* clubroot	Clubroot declines more quickly when grown in rotation with cucurbits, tomato, snap bean or buckwheat.
Corn	*Increase* corn rootworm	Corn rootworm adults are attracted to cucurbits. They lay their eggs at the base of the plants and the larvae attack corn roots the following year.
Lettuce, spinach, brassica greens	Possible double cropping	Cucurbits can be double cropped when planted after early salad crops or brassica greens.
Hairy vetch	Early seeding of cover crop	Hairy vetch can be overseeded into winter squash in July to provide a winter cover crop after harvest.

Excerpt from Appendix 2 of Crop Rotation on Organic Farms: A Planning Manual. Charles L. Mohler and Sue Ellen Johnson, editors. (Link 18)

Source: *Resource Guide for Organic Insect and Disease Management. Crop Management Practices – Cucurbits.* http://web.pppmb.cals.cornell.edu/resourceguide/cmp/cucurbit.php. (Adapted from the Cornell Pest Management Guidelines for Vegetables).

Management of Nematodes (USA Cucurbits)

Primarily Northern root-knot (*Meloidogyne hapla)* and root-lesion *(Pratylenchus spp.)*

Time for concern: Before planting. Long-term planning is required for sustainable management.

Affected crop(s): All cucurbits

Key characteristics: In the field, plants severely infected with either nematode generally lack vigor, are stunted and can be chlorotic. Belowground, galls develop on the roots of plants infected by root-knot nematode that disrupt the uptake of nutrients and water by the roots, while the root-lesion nematode does not cause any specific symptoms on the roots.

Management Option	Recommendations for Nematodes
Scouting/thresholds	Use a soil bioassay with lettuce and/or soybean to assess soil root-knot and root-lesion nematode infestation levels, respectively. Or, submit the soil sample(s) for nematode analysis at a public or private nematology lab (Link 44). See Section 4: Field Selection for more information as well as the following Cornell publications for instructions:
Resistant varieties	No resistant varieties are available.
Crop rotation	Root-knot nematode has a wide host range but grain crops including corn, wheat, barley and oat are non-hosts and therefore effective at reducing the nematode population. If both root-lesion and root-knot nematodes are present in the same field then rotation with a grain crop may increase the root-lesion nematode population to a damaging level for the next crop. In addition to grain crops, root-lesion nematode has over 400 hosts including many vegetables that are planted in rotation with cucurbits thus making it difficult to manage root-lesion nematode strictly using a crop rotation. Depending on the size of the infested site, marigold varieties such as 'Polynema' and 'Nemagone' are very effective at reducing nematode populations, where marigold can be established successfully.
Site selection	Assay soil for nematode infestation, if needed.
Biofumigant cover crops	Grain cover crops such as winter rye and oat are poor or non-hosts for the root-knot nematode, thus they are effective at reducing the population. Cover crops with a biofumigant effect, used as green manure are best used for managing root-lesion nematode and will also reduce root-knot nematode populations. It is important to note that many biofumigant crops including Sudangrass, white mustard, and rapeseed are hosts to root-lesion nematode and will increase the population until they are incorporated into the soil as a green manure at which point their decomposition products are toxic to nematodes. Research has suggested that Sudangrass hybrid 'Trudan 8' can be used effectively as a biofumigant to reduce root-lesion nematode populations. Cover crops such as forage pearl millet 'CFPM 101' and 'Tifgrain 102', rapeseed 'Dwarf Essex', and ryegrass 'Pennant' are poor hosts, and thus will limit the build-up or reduce root-lesion nematode populations when used as a "standard" cover crop.
Sanitation	Avoid moving soil from infested fields to uninfested fields via equipment and vehicles, etc. Also limit/avoid surface run-off from infested fields.
Weed Control	Many common weeds including lambsquarters, redroot pigweed, common purslane, common ragweed, common dandelion and wild mustard are hosts to root-lesion nematode; therefore effective weed management is also important.

Source: *Resource Guide for Organic Insect and Disease Management. Crop Management Practices – Cucurbits.* http://web.pppmb.cals.cornell.edu/resourceguide/cmp/cucurbit.php. (Adapted from the Cornell Pest Management Guidelines for Vegetables).

Management Strategies for Less Commonly Occurring Cucurbit Diseases (USA)

Disease	Are Resistant Varieties Available?	Rotation out of Cucurbits	Is Disease Seed-borne?	Site Selection
Alternaria leaf blight	No	2 yr	Yes	Choose sites that favor fast leaf drying. Schedule overhead irrigation so it doesn't extend overnight leaf wetness. Avoid planting next to other cucurbits.
Angular and bacterial leaf spot	C	2 yr	Yes	Avoid planting next to other cucurbits
Anthracnose	C	2 yr	Yes	Not a viable management option
Belly rot	No	NE	-	Avoid soils that don't drain well
Choanephora blossom blight and fruit rot	No	2 yr	No	Allow for good air drainage; avoid dense plantings
Cottony leak *Pythium* spp	No	NE	No	Choose well-drained sites, avoid excessive overhead irrigation
Damping off and root rot *Pythium* spp	No	NE	No	Not a viable management option
Fusarium wilt, Fusarium crown rot, Verticillium wilt	No	5 yr *	Yes	Not a viable management option
Gummy stem blight and black rot	No	2 yr	Yes	Not a viable management option
Plectosporium blight	No	2 yr	No	Avoid soils that don't drain well. Not a threat for cucumber or butternut squash.
Scab	C	2 yr	Yes	Select sites that have well-drained soils and are conducive to good air movement. Avoid planting next to other cucurbits
Sclerotinia white mold	No	4 yr*	No	Avoid fields with a history of white mold. Avoid dense plantings that hold humidity. Sclerotinia has a wide host range.
Seed-borne diseases and seed decay	No	NE	Yes	Do not plant into cool, wet soils. Select areas that are well-drained.
Septoria leaf spot	No	2 yr	No	Only affects winter squash
Ulocladium leaf spot	C	2 yr	No	Only affects cucumbers
Viruses (PRSV, WMV, CMV, ZYMV)	C	NE	No	Plant late-season fields as far away from existing cucurbits as possible. A weed-free zone around the field may reduce the incidence of CMV and WMV. Reflective mulches or floating row covers may help repel or exclude aphids

C-Cucumber, NE-Not Effective, *Because of the wide host range, rotate away from cucurbits and other susceptible crops. PRSV=Papaya Ringspot Virus, CMV=Cucumber Mosaic Virus, WMV=Watermelon Mosaic Virus, ZYMV=Zucchini Yellow Mosaic Virus.

Source: *Resource Guide for Organic Insect and Disease Management. Crop Management Practices – Cucurbits.* http://web.pppmb.cals.cornell.edu/resourceguide/cmp/cucurbit.php. (Adapted from the Cornell Pest Management Guidelines for Vegetables).

Examples of "How To" Nematode Guides

Abawi, F.S., Gugino, B.K. (2007) Cornell University, New York State Agricultural Experiment Station.. *Soil Sampling for Plant-Parasitic **Nematode Assessment**.* (http://www.nysaes.cornell.edu/recommends/Nemasoilsample.pdf).

Cornell University, New York State Agricultural Experiment Station. *Visual Assessment of **Root-Knot** Nematode Soil Infestation Levels Using a Lettuce Bioassay.* (http://www.nysaes.cornell.edu/recommends/Rootknotnemahowto.pdf).

Gugino, B.K., Ludwig, J.W., Abawi, G.S., Cornell University, New York State Agricultural Experiment Station. *A Soil Bioassay for the Visual Assessment of Soil Infestations of **Lesion Nematode**.* (http://www.nysaes.cornell.edu/recommends/Lesionnemahowto.pdf).

Source: *Resource Guide for Organic Insect and Disease Management. Crop Management Practices – Cucurbits.* http://web.pppmb.cals.cornell.edu/resourceguide/cmp/cucurbit.php. (Adapted from the Cornell Pest Management Guidelines for Vegetables).

Grower decision support for using rootstocks for wine grapes in the absence of phylloxera

QUESTIONS TO ASK			Enter your score here
SOIL FACTORS			
Nematodes?			
- Previous use?			
Non horticulture	Vegetable or other crops susceptible to nematodes	Vines	
1	10	10	
- Topsoil soil texture?			
Clay	Loam	Sand	
1	3	10	
- Tests for root-knot nematodes?			
None present	Some present	Lots present	
1	10	20	
pH of soil?			
- Acidity?			
About neutral; 7	5 – 7	< 5	
1	2	5	
- Alkalinity (Lime)?			
About neutral; 7	7 – 8	> 8	
1	2	5	
SALINITY			
Irrigation water?			
< 1 dS/m (1000 EC)	2 dS/m (2000 EC)	4 dS/m (4000 EC)	
1	3	10	
Soil salinity?			
Low	Medium	High	
1	5	10	
OTHER FACTORS			
Drought tolerance needed?			
Vineyard dry grown	Limited water	Plenty of water	
5	2	1	
Winery opposition to rootstocks on quality grounds?			
Oppose	Not sure	No opposition	
1	3	5	
Vigour management (low or high)?			
Not a problem	Not sure	Problems anticipated	
1	3	5	
Total all the scores from the boxes		YOUR TOTAL	

BENEFITS OF USING ROOTSTOCKS IN ABSENCE OF PHYLLOXERA?

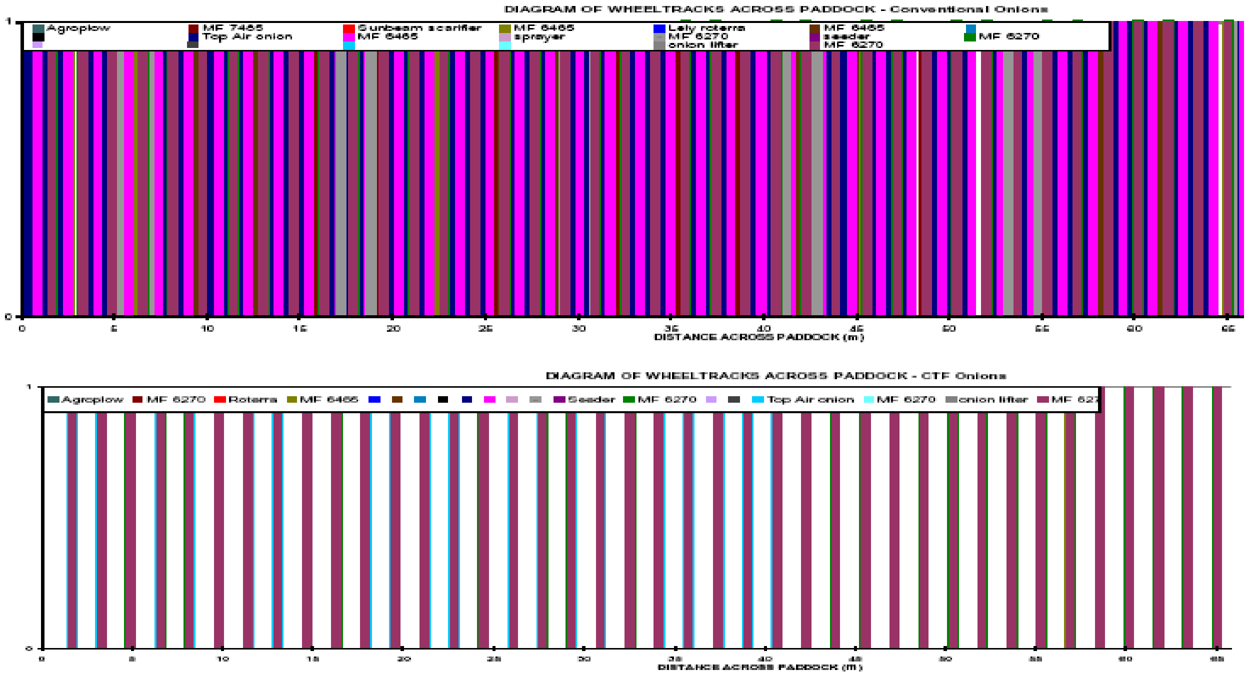
Score	0 – 20	21 – 35	36 – 75
Benefit	Low	Medium	High

Source: Scholefield Robinson and EconSearch, 2002. Rootstock Analysis Planting Tool, PGIBSA.

APPENDIX 3B

Compaction potential in vegetable production

Diagram of wheel tracks across paddock – Conventional onions (top) and CTF onions (bottom)



Conventional = 95% track area

CTF = 28% track area

Source: McPhee, 2012, CTF Presentation