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## **Influence of Rotation and Biofumigation on Soil-Borne Diseases of Potatoes**

Rudolf de Boer *et al*  
Department of Primary  
industries, Victoria

Project Number: PT96032

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# Influence of rotation and biofumigation on soil-borne diseases of potatoes

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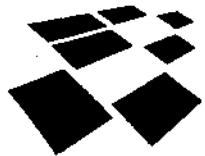
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**Horticulture Australia**

## Horticulture Australia Project PT96032

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### Purpose of project

The purpose of this project was to evaluate the influence of crop rotation practices on soil-borne pathogens, diseases and yields of potatoes in Australia. Potato diseases have become persistent and costly problems for most potato growers, even for those who supposedly practice good rotations. The aim was to also evaluate the importance of *Brassica* crops in rotations and determine if their 'biofumigation' potential could reduce the levels of the soil borne diseases affecting potatoes.

### Acknowledgments

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**January 2003**

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## 1 Media Summary

This project is the first major study of the influence of crop rotation on disease and yield of potatoes in Australia. The study concludes that a large proportion of the Australian potato crop is grown in rotations that exceed the minimum 2-3 year break recommended by overseas researchers. Many crops are grown after long-term pastures, which, if managed well, can replenish soil nitrogen and restore soil structure and theoretically break the life cycle of soil-borne potato pathogens. However, our research has found that some of these pathogens can persist in these systems because they produce dormant spores capable of surviving in soil for many years without potatoes, or can exploit hosts other than potatoes in the rotation. Their effective management will depend on the long-term management of rotations based on a sound knowledge of the life cycle of the potato pathogens in the rotation.

A survey of commercial potato crops (Russet Burbank) in a major production area of Victoria did not find a clear relationship between the duration of the break between potato crops (1-2 years or 5-6 years), the common diseases (e.g. Rhizoctonia canker, black scurf, black dot, powdery scab) and yield of potatoes. This suggested that some pathogens could survive the pasture phase. Some of the lowest levels of disease and the best yields were in fields cropped every three years, whereas, some of the poorest yields were in fields cropped only every five or more years. Although rotation was one factor affecting disease in some crops, other factors also had a major impact on disease and yield in some crops. Average yields ranged from 33-64 tonnes per hectare, highlighting the potential for considerable improvement in yields on some farms.

Four rotation trials were conducted in Victoria and South Australia to evaluate the impact of different crop species in rotation with potatoes (one to three cycles) on disease and yield. The crops included mixed pasture, clover, perennial ryegrass, wheat, oats, barley, buckwheat, cereal rye, fodder and mustard seed *Brassica* varieties and white radish. Overall, these rotations did not have a major impact on disease levels. Variations in yields between different rotations (up to 30%) in some seasons could not be linked to particular crop types, such as *Brassica*, cereals or pasture. This agrees somewhat with overseas studies where cropping frequency in the same field was found to have a greater impact on disease and yield than the type of crop grown before potatoes.

There was little evidence in the field trials of significant reductions in disease levels when varieties of *Brassica* crops with different 'biofumigation' potential were ploughed-in as green manure crops before potatoes, or when Indian mustard seed meal was incorporated into soil before potatoes. This was despite laboratory tests which showed that chemicals released from *Brassica* tissues and the mustard meal could inhibit the growth of organisms that caused Rhizoctonia canker, black scurf, black dot, Verticillium wilt and pink rot.

One reason for this is that *Brassica* can host some of the potato pathogens. We found the potato strain of *Rhizoctonia solani*, which causes stem canker and black scurf (anastomosis group AG3), actively growing and reproducing in the roots of fodder and mustard *Brassica* and also on red clover. A second strain, AG2, which is usually associated with legumes and *Brassica*, was also found in lesions on potato stems and on the roots of clover and *Brassica*. In glasshouse tests, this strain not only damaged clover and *Brassica*, but also caused severe stem canker in potatoes. This is the first report of the AG2 strain causing serious damage to potatoes. In all, we identified the strains AG3, AG 2 (2-1 and 2-2), AG4 and AG5 in potato crops in Victoria, with AG3 accounting for about two thirds and AG2 for one quarter of the total numbers identified.

## 2 Technical Summary

Laboratory, glasshouse and field trials were conducted in Victoria and South Australia to evaluate the influence of rotation practices on soil-borne pathogens, disease and the yield of potatoes. A systematic survey of 16 commercial Russet Burbank crops in Victoria did not find a correlation between the duration of the 'break' period between potato crops (1-2 years or 5-6 years pasture) and disease and yield. Some of the highest levels of disease were recorded in crops with a relatively long break (5-6 years) from potatoes. It was concluded that other variables, besides cropping history, had a major impact on disease and yield. Rhizoctonia canker was the most common disease in the growing crop (1-76% plants affected), whilst black dot the most common tuber disease (0-30% tubers affected). Average yields ranged from 33-64 t/ha, highlighting the potential for considerable improvement in yield on some farms.

Four rotation trials were conducted in Victoria and South Australia in which different crop species (mixed pasture, clover, perennial ryegrass, wheat, oats, barley, buckwheat, cereal rye, different varieties of fodder and mustard seed *Brassica* and white radish) were rotated with potatoes over one to three cycles. In some trials and some seasons, disease incidence and severity in the crop and on tubers varied with rotation treatments. Similarly, yields varied by up to 30% between some treatments. However, there were no consistent patterns correlating the type of crop grown prior to potatoes (cereal, *Brassica*, pasture) or particular rotation sequences, with variations in disease and yields.

In studies of the 'biofumigation' potential of *Brassica*, volatile chemicals from Indian mustard seed meal and from the tissues of field-grown *Brassica napus* and *Brassica juncea* plants inhibited the growth of the fungal pathogens *Rhizoctonia solani* (AG3 and AG8), *Verticillium dahliae*, *Colletotrichum coccodes*, *Phytophthora erythroseptica* and *P. cryptogea* *in vitro*. The degree of inhibition depended on the fungus and the plant material. Leaves sprayed with the herbicide glyphosate were less toxic than unsprayed leaves. Seed meal of *B. juncea* was more toxic than the leaves of the plant. Generally, the *Phytophthora* species were the most sensitive, *C. coccodes* the least sensitive and *V. dahliae* and *R. solani* intermediate in sensitivity to the volatile products. Furthermore, *R. solani* AG8 tended to be more sensitive than *R. solani* AG3. Despite this, there was generally little evidence in field trials of significant reductions in disease incidence and severity from the ploughing-in of *Brassica* green manure crops with differing biofumigation potential or Indian mustard seed meal before potatoes. The mustard meal, however, proved to be phytotoxic to potatoes in one trial, retarding both emergence and growth.

*Rhizoctonia solani* anastomosis groups (AG) 3, 2-1, 2-2, 4 and 5 were identified in a systematic study of the fungus in rotations in Victoria. Over 60% of the isolates taken from stem lesions belonged to AG3, the so-called 'potato attacking strain', and 26% to AG2 (mostly 2-1) which is usually associated with legumes and *Brassica*. The majority of isolates taken from sclerotia on tubers, however, belonged to AG3. In glasshouse tests, the AG2 isolates were very pathogenic to stems, stolons and tubers of potatoes, but produced few, if any, sclerotia on tubers. This contradicts reports of overseas studies that found the AG2 group to be only mildly pathogenic or non-pathogenic to potatoes. The Australian isolates were highly pathogenic to fodder rape, Indian mustard and red clover but not to perennial ryegrass. The AG3 isolates, on the other hand, were pathogenic to potatoes but not ryegrass, red clover and *Brassica* spp. In the field, however, the AG3 isolates colonised the roots of clover and the *Brassica*, producing abundant sclerotia on the latter, establishing an epiphytic relationship with these hosts. This indicates that pasture and *Brassica* crops will not be an effective disease break for *R. solani*.

This study concludes that a large proportion of the Australian potato crop is grown in rotations that exceed the minimum recommended break of 2-3 years. Pathogens persist in these systems because they can exploit other hosts or produce dormant spores. Their effective management will depend on the long-term management of the rotations based on a better understanding of the life cycle of the potato pathogens in the rotation.

### 3 The influence of crop rotation on soil-borne diseases of potatoes – an overview

#### 3.1 Introduction

There are few places in Australia, apart from the Albany Swamps in Western Australia and the Koo Wee Rup Swamp in Victoria, where potatoes are cropped year after year without a break. In many production areas, potatoes are grown after a pasture phase of two or more years in mixed enterprises involving livestock. Regulations for certified seed potato production stipulate that early generation seed (G1-G3) can only be grown after a minimum five-year break from potatoes and a minimum three-year break for later generations (G4-G5). For commercial cropping, a minimum break of two to three years is recommended. The potato-free periods are recommended to essentially minimise disease risk and allow the control of volunteer potatoes.

Diseases are persistent and costly problems for the potato industry and as there has been little research on rotations in potato cropping in Australia, there is a general lack of knowledge of how rotation practices influence disease and yield.

The objectives of this project were to:

- Evaluate the influence of rotations on soil-borne pathogens, diseases and yield in major potato production districts; and to
- Evaluate the biofumigation potential of *Brassica* in suppressing soil-borne pathogens and in reducing diseases in the field.

The research program was conducted in Victoria and South Australia and involved:

- surveys of commercial crops to determine if there were any relationships between cropping history and disease and yield;
- field trials in which different crop species such as *Brassica*, cereals, pastures and the individual components of pasture were grown in rotation with potatoes;
- Laboratory, glasshouse and field trials to explore the biofumigation potential of *Brassica* in potato cropping; and
- Studies of how potato pathogens are influenced by rotations.

The project was originally conceived as a collaborative effort between scientists from of the Department of Primary Industries, Victoria (formerly Natural Resources and Environment), the South Australia Research and Development Institute, Adelaide and New South Wales Agriculture, Yanco (Len Tesoriero and Andrew Watson). However, due to changes within the NSW Agriculture and movement of staff to other Institutions, the contribution from these scientists was limited to the first year of the project.

## 3.2 Why use crop rotation?

### 3.2.1 Crop rotation in history

Crop rotation is an ancient practice. History has taught us that practicing crop rotation ensures that soils remain healthy and productive. In Peru before the arrival of the Spanish, the Inca Indians practiced a seven-year rotation for potato that was enforced by law (Glass and Thurston 1978). The Inca must have learnt through centuries of trial and error that this rotation gave the best results. We now know that the potato cyst nematodes *Globodera pallida* and *G. rostochiensis* are present in extremely high levels in most potato growing areas of the Peru. A seven-year rotation reduces potato cyst nematode populations below their economic threshold. What may have appeared to be a senseless custom to the Spanish was effective pest control in practice.

### 3.2.2 Crop rotation in Australia

Crop rotation is an essential component of sustainable cropping systems. Rotations allow versatility in source and stability of income in the mixed enterprise farming systems practiced in Australia. In many areas, potatoes are regularly cropped after long-term pastures in mixed enterprise systems, with pastures supporting livestock, often dairy cattle or sheep.

Potatoes were traditionally grown in areas with cool climates and high rainfall. The development of irrigation systems over the past twenty years has allowed the expansion of potato production into marginal areas on the periphery of traditional cropping areas or into semi-arid regions once used exclusively for field crops and sheep. As a consequence, potatoes can be grown as summer or winter crops in some areas. A recent trend in the industry is for potato growers to lease 'new' land not previously used for potato cropping, often where dairy or field crops are produced.

**Table 1 Examples of potato rotations in Australia**

Location	Rotations
Albany Swamps, WA	Continuous potato cropping with winter floods
Koo-Wee-Rup, Vic	Continuous potatoes intercropped with cereal rye as a green manure 4-years pasture-potatoes
Gippsland, Vic	6-years pasture, 3 years potatoes intercropped with cereal rye 2 or more years pasture – potatoes-cereal rye-pasture
Central Highlands, Vic	2 or more years pasture-potatoes-cereal/ <i>Brassica</i> /cereal rye- pasture
Simpson, Vic	20 years pasture-potatoes-pasture
Mt Gambier, SA	7 to 20 years pasture-potatoes
Mallee, SA	<b>Virgin ground (cereal, pasture)-potatoes</b> Onions-cereal-potato-cereal-carrots
Virginia, SA	Potatoes-fallow-potatoes Potatoes-fallow-carrots-fallow-potatoes Potatoes-fallow-carrots
North Coast of Tasmania	Potatoes rotated with peas, poppy, onions, pasture, pyrethrins and other vegetable crops

Examples of rotations in potato production are presented in Table 1. Common rotations in Victoria are based on two to several years of a pasture phase, followed by a potato crop, after which one or two consecutive crops of oilseed *Brassica*, fodder *Brassica*, cereals, legumes or green manures may be grown before pastures are sown down again. Pastures are clover-based (red, white and sub). Legume based pastures grown for 5-8 years accumulate nitrogen (Ellington 1986) and restore soil structure after the cropping phase. Anecdotal evidence from the Central Highlands region of Victoria (Ballarat), where the processing variety Russet Burbank is grown on volcanic loams, indicates that a second consecutive potato crop after pasture leads to a noticeable deterioration of soil structure.

Examples of different crops grown in rotations in other countries are shown in Table 2. In Wisconsin in the US, land is devoted entirely to cropping, presenting growers with different challenges to Australian farmers who run mixed enterprises involving pastures and potatoes.

**Table 2 Examples of crops commonly rotated with potatoes in Australia and other countries**

Australia	Wisconsin, USA	Prince Edward Island, Canada	The Netherlands
2 or more years <sup>1</sup>	3-4 years	3 years optimum	3-4 years
<i>Pasture (2 or more years)</i>	<i>Processing crops</i>	<i>Pasture</i>	<i>Cereals</i>
Grasses & Clovers	Green peas	Annual ryegrass	Wheat or Barley
<i>Cereals</i>	Snap beans	Red clover	Oats
Wheat, Oats, Barley	Sweet corn	<i>Cereals</i>	Maize
<i>Legumes</i>	<i>Field Crops</i>	Winter wheat or barley	<i>Processing crops</i>
Lucerne, Lupins, Peas	Field & seed corn	(Optimum: potato-barley under seeded with red clover)	Sugar beet
<i>Oilseed</i>	Alfalfa		
Canola	Soybean		
<i>Fodder</i>			
Rape, Swede, Turnip			
<i>Green manure crops</i>			
Ryecorn			
<i>Vegetables</i>			
(Only in some districts.)			

<sup>1</sup> Potatoes are usually sown after 2 or more years of pasture. Other crops are grown after potatoes.

### 3.2.3 The importance of cropping frequency on disease, yield and quality of potatoes

Overseas research has shown that increasing the frequency of cropping potatoes in a rotation (i.e. shorter and shorter rotations) increases the risk of poor yields (Table 3). In long-term trials, continuously cropped potatoes initially yielded as well as potatoes in a rotation, but eventually (after 2-3 or 5-7 seasons depending on the site) yields dropped (Vos and Van Loon 1989). In trials in which a range of cropping frequencies were studied, (eg. 2, 3, 4, 5 or 6 course rotations), yields were reduced as cropping frequency increased. In long-term trials in the Netherlands, potatoes cropped once in every six years, once in every four years or once every three years yielded 7%, 16% and 20% less, respectively, than potatoes grown for the

first time in a 'new' field (Lamers *et al.* 1989). Diseases caused by nematodes and fungi were major factors contributing to yield loss in trials around the world (van Loon 1992; Bollen *et al.* 1989; Vos and Van Loon 1989).



**Table 3 Effect of cropping frequency on the yield of potatoes – a summary of data from long-term field trials (Vos and Van Loon 1989)**

Frequency of potato cropping (years)	Reduced cropping frequency	Yield reduction (%)	Country
Control			
First crop	1:6	7%	Netherlands
Potatoes 1:6 years	1:4	6%	
First crop	1:3	20%	
1:6	1:3	15%	
1:3	Continuous cropping	30%	
1:4	1:3	2%	Germany
1:4	1:2	8%	
1:4	Continuous cropping	30%	
1:3	Continuous cropping	19%	Canada
1:2	Continuous cropping	27%	
1:2	Continuous cropping	14%	USA

Cropping frequency can affect tuber quality. In studies in eastern Canada, reducing the length of rotations to less than 3 years (considered the optimum at present) resulted in marked increases in the proportion of processing potatoes culled at the factory gate. Most of this cullage was related to poor tuber size, misshapen and diseased tubers. A 2-year rotation was not sustainable because increases in cullage resulted in a net loss in income to the grower (Carter 1996).

Current research suggests that reduced yields associated with short rotations or continuous cropping cannot be alleviated with an input of additional mineral fertiliser and organic matter or by any other cultural practices (Lamers *et al.* 1989; Vos and Van Loon 1989).

### 3.2.4 Is there a minimum break for potatoes?

Clearly the advice is, the longer the rotation the better. Optimum rotations will obviously depend on soil type, climate, crop species grown, disease pressure and economics. Conventional wisdom indicates that in many cropping areas, potatoes should not be grown more frequently than once in every 3-5 years (Carter 1996; Carter and Sanderson 2001; Scholte 1992). Growers in two particular districts (Koo Wee Rup Swamp, Victoria and the Albany Swamps, Western Australia) practice continuous cropping of potatoes for up to 20 years. Most claim to produce satisfactory yield and quality. Some growers grow three potato crops in succession after six years of pasture. The challenge is to determine why these farms do not have serious problems with disease and yield and whether changing these practices will actually improve yields.

### 3.2.5 The principals of disease control with rotations

The aim of good rotation is to sustain optimum yields and quality. Rotations are practiced to maintain soil structure and health and manage pests and diseases.

#### Maintenance of soils by:

- the promotion of good soil structure (especially after leys, fodder crops and green manure);
- the maintenance of the soil's capacity to self regulate (buffering);
- a balanced organic matter content to sustain high biological activity;
- minimising the leaching of nutrients;
- ensuring a good supply of available nitrogen (from forage and grain-legumes) and
- minimising erosion (Keller 1989; Sieczka 1989; Carter and Sanderson 2001).

#### Pest and disease management by:

- interrupting the life-cycle of diseases and pests by growing non-host crops in between potato crops (disease 'break');
- preventing the build-up of soil populations or by reducing the populations of pathogens and pests;
- allowing efficient weed control (Keller 1989; Sieczka 1989) and
- promoting soil microbial diversity (Carter and Sanderson 2001; Sturz *et al.* 1997; van Overbeek *et al.* 2002).

The survival and activity of pathogens in soil and the development of disease depend on a complex ecological interaction. The life cycle and survival mechanisms of each pathogen is determined by environmental conditions and the access to the host.

Pathogens can be divided into different groups by the nature of their mode of survival and their life cycle.

- Obligate parasites require a living host to complete their life cycle. They often have a very limited host range but may survive in soil for long periods without a host (e.g. *Spongospora subterranea* causing powdery scab).
- Pathogens with a saprophytic stage, surviving in organic matter, actively growing in soil or colonising the roots and stems of plants without causing disease, and a parasitic stage in which they infect plant tissues and cause disease (e.g. *Rhizoctonia solani*).
- Root-inhabiting pathogens that are more specialised and have a transitory existence in soil (eg. root knot nematode and root lesion nematode).

#### 'Break' crops

Rotating crops with non-hosts is said to 'break' the life cycle of some pathogens. In theory, a pathogen is unable to survive without its host and its population in the soil gradually decreases over time. A 'break' prevents the excessive build-up of populations of pathogens.

In practice, the effectiveness of a break crop depends on the life cycle and survival mechanisms of the pathogen and host range (different species of crop plants or weeds).

For example, the potato cyst nematode and the powdery scab fungus *Spongopora subterranea*, both have a relatively narrow host range (Brodie 2001; Christ 2001). As obligate parasites, they complete their life cycle only in presence of a live host. However, the cysts of the potato cyst nematode and cystosori of *S. subterranea* are able to survive in soil in a dormant state for several years without a host.

In reality, many pathogens are able to colonise the roots and stems of plant species other than potato, thereby maintaining populations at low levels in the absence of potatoes. *Rhizoctonia solani*, *Colletotrichum coccodes* (black dot) and *Verticillium* are examples of such pathogens. Providing a break from potatoes and other host crops or host weeds minimises the build up of populations of those pathogens.

### **Soil biology, structure and nutrients**

Frequent cropping can damage soil structure, impede drainage, reduce organic matter, nutrients and the level of natural flora and fauna, reduce plant vigour and increase the susceptibility of hosts to damage by pathogens.

#### *Soil organic matter*

Research in Canada has shown that potatoes add relatively little root residue (about 300 kg/ha) to the soil, compared with cereals (1500-2500 kg/ha) or grasses (3000-5000 kg/ha). The use of short rotations for potato cropping will lower soil organic matter and soil quality in general, leading to high potential for soil degradation and erosion (Carter 1996).

#### *Soil structure*

Destroying soil integrity (soil aggregates and structure) and impeding drainage can favour some pathogens. Poor drainage can increase the risk of outbreaks of powdery scab and pink rot because prolonged periods of high soil moisture favour the activity of the pathogens causing these diseases. Poor soil structure in general can reduce crop growth, thereby making plants more susceptible to damage by pathogens.

Some crops, by nature of their rooting pattern and rooting depth, can have beneficial effects on soil structure system. Lupins and other legumes, for example, are often called 'biological ploughs' because of their beneficial effects on soil structure. Long-term pastures have positive effects on soil structure.

#### *Soil nutrients*

Some crops, such as legumes improve soil nitrogen and encourage the build-up of populations of soil micro-organisms that can inhibit the activity of some pathogens. Good plant vigour resulting from good soil nutrition minimises the effects of damage by *Rhizoctonia* and *Colletotrichum* or reduces the susceptibility potato plants to target spot, for example. Well managed pastures in potato rotations can restore soil nitrogen and structure. On the other hand, some rotations may favour the activity of pathogens by enhancing their survival or by inhibiting natural antagonists.

### **3.3 Biofumigation - using biocides from *Brassica* spp. to suppress diseases**

The leaves, stems and roots of various *Brassica* and related genera contain substances called glucosinolates. When plant tissues degrade these chemicals are hydrolysed by enzymes into bitter tasting, toxic and goitrogenic compounds which include various forms of isothiocyanates (ITC's) (Fenwick *et al.* 1983; Brown *et al.* 1991). It has been known for some time that these compounds have fungicidal, nematicidal, bactericidal and insecticidal properties (Angus *et al.* 1994; Kirkegaard *et al.* 1996; Sarwar *et al.* 1998). Methyl isothiocyanate, for example, is a breakdown product of the synthetic, commercial fumigant Metham sodium. Until recently, the biocidal properties of ITCs from *Brassica* in natural systems had not been exploited. There has been a renewed interest in using these special properties of *Brassica* in crop rotations around the world. CSIRO scientists coined the term 'biofumigation' to describe the concept of using natural fumigants from plants to control pathogens.

The relative concentrations of glucosinolates (GSL) that liberate ITCs (the 'biofumigation' potential) vary considerably between and within the various species of *Brassica* used in agriculture (Kirkegaard and Sarwar 1998; Sarwar and Kirkegaard 1998). The types of GSLs in leaves are different to those in the roots. The different types of GSs present within species are similar, but vary between species. *Brassica napus*, *B. campestris* and *B. oleracea* are high in GSLs that do not release ITCs, whereas *Brassica nigra*, *B. carinata*, *B. juncea* and *Brassica* weeds have mainly GSLs that liberate ITCs. Plants produce peak concentrations of GSLs around flowering and levels tend to be higher in plants grown in the spring and summer than in the cooler times of the season.

#### **The 'biofumigation' potential of *Brassica***

There have been several studies in Australia and overseas demonstrating toxicity of volatile compounds from *Brassica* to bacteria, fungi, nematodes and insects. Some examples are listed in Table 4. Most of this information comes from laboratory tests, pot trials or micro-plot trials. There are few examples that demonstrate the biofumigation in the practice. Kirkegaard *et al.* (1998) provide evidence that suppression of take-all disease in wheat grown after canola (*B. napus*) or Indian mustard (*B. juncea*) is correlated with concentrations of GSLs in the *Brassica*. The *Brassica* were more suppressive than linseed and the degree of suppression increased with increasing concentrations of GSLs in the *Brassica*. Previous *in vitro* studies had identified the take-all fungus as being the most sensitive to volatiles from *Brassica* tissues compared with *Rhizoctonia*, *Pythium*, *Biopolaris* and *Fusarium* (Kirkegaard *et al.* 1996).

#### **Evaluating biofumigation against potato pathogens and diseases**

Our studies showed quite clearly that volatile compounds released from *Brassica* tissues inhibited the growth of *Rhizoctonia solani* (AG3 and AG8), *Colletotrichum coccodes*, *Verticillium dahliae*, *Phytophthora erythroseptica* and *Phytophthora cryptogea* (Section 4.3). In an overseas study, the growth of another potato pathogen, the potato dry rot fungus (*Fusarium sambucinum*), was also inhibited by volatile chemicals from *Brassica* (Mayton *et al.* 1996). The relative sensitivity of the different pathogens we tested varied, as did the sensitivity of the cereal pathogens reported by Kirkegaard *et al.* (1996).

A variety of *Brassica* crops were planted in field trials in Victoria and South Australia and ploughed-in as green manures prior to planting potatoes. Some of these crops were planted in a three-year cycle of *Brassica*-potato (Table 5, Table 12, Table 14, Table 18, Table 19 and Table 20). Generally, there was little evidence to indicate that *Brassica* crops in particular suppressed disease.

**Table 4. Some examples of pathogens or insects affected by ITCs from *Brassica* tissue in laboratory, glasshouse and micro-plot experiments**

Host	Pathogen/disease/insect	Common name	References	Country
<i>In-vitro tests</i>				
Cereals	<i>Gaeumannomyces graminis</i> var <i>tritici</i>	Take-all	Angus <i>et al.</i> 1994; Kirkegaard <i>et al.</i> 1996	Australia
	<i>Fusarium graminearum</i>	Crown rot	Kirkegaard <i>et al.</i> 1996	Australia
	<i>Pythium irregularare</i>	Root rot	Sarwar <i>et al.</i> 1998	Australia
	<i>Bipolaris sorokiniana</i>	Common root rot	Kirkegaard <i>et al.</i> 1996	Australia
	<i>Rhizoctonia solani</i>	Root rot	Kirkegaard <i>et al.</i> 1996	Australia
Potato	<i>Fusarium sambucinum</i>	Dry rot	Mayton <i>et al.</i> 1996	USA
Oilseed rape	<i>Leptoshaeria maculans</i>	Black leg	Mithen <i>et al.</i> 1986	UK
Potato/ Vegetable	White fringed weevil, Garden weevil		Matthiessen <i>et al.</i> 1996	Australia
<i>Pot &amp; micro-plot tests</i>				
Potato	<i>Ralstonia solanacearum</i>	Bacterial wilt	Akiew <i>et al.</i>	Australia
Potato/ vegetables	<i>Meloidogyne chitwoodii</i>	Root-knot	Mojtahedi <i>et al.</i> 1991	USA
	<i>Meloidogyne hapla</i>			
Canola	<i>Pratylenchus neglectus</i>	Root lesion nematode	Potter <i>et al.</i> 1999	Australia
Peas	<i>Aphanomyces eutiches</i>	Root rot	Chan <i>et al.</i> 1987, Lewis <i>et al.</i> 1971	USA

**Table 5 *Brassica* species with differing biofumigation potential grown prior to potatoes in rotation field trials in Victoria and South Australia**

Fodder rape ( <i>Brassica napus</i> L.) cv. Hobson
Fodder rape ( <i>Brassica napus</i> L.) cv. Striker
'Biofumigation' <i>Brassica</i> ( <i>Brassica napus</i> L., <i>Brassica campestris</i> L.) 'BQ Mulch'®
'Fodder' <i>Brassia</i> ( <i>Brassica napus</i> ) 'BQ Fodder'®
Indian Mustard ( <i>Brassica juncea</i> (L.) Czern.) 'Nemfix'®
White radish ( <i>Raphanus sativus</i> ) 'Weedcheck'®

The concept of biofumigation has caught grower's imaginations and there is an assumption that ploughing-in a *Brassica* crop before potatoes will result in dramatic reductions in disease in the potato crop. However, there are many complicating factors at play that can influence the outcomes. They include soil type (physical structure, pH, chemistry,), soil conditions (moisture, temperature, organic matter content), type of pathogen, whether the *Brassica* is a host of the target pathogen, the amount of biomass produced by the *Brassica*, the type of ITCs produced and their concentrations in the plant.

#### *Biofumigation and the soil environment*

Soil condition is an important factor affecting the efficacy of ITCs. Soil must be worked to a fine tilth, have a relatively low organic matter content and must be relatively warm and moist

for effective fumigation with the commercially manufactured ITC, Metham sodium. The fumigant is more effective in sandy soil than in heavier soils. Higher rates of application are required in clay loams with a high organic matter content. The effectiveness of natural volatile compounds released from decaying *Brassica* residues will also be governed by these factors. Also, the concentration of ITCs released in soil when *Brassica* residues are ploughed-in may only be one tenth of that from commercial fumigation with Metham sodium (J Nichols personal communication).

#### *Are potato pathogens good candidates of biofumigation?*

The take-all fungus in cereal crops is a particularly good candidate for control with break crops, especially so with *Brassica* because it is particularly sensitive to ITC's (Angus *et al.* 1994; Kirkegaard *et al.* 1998). It has a very narrow host range, survives in the debris of grasses and cereals and has limited ability as a saprophyte in soil. *Brassica* species are not hosts.

Other pathogens may not be good candidates for biofumigation. *R. solani*, for example, occurs in soil as thick walled melanised hyphae and sclerotia. It is a good saprophyte, readily colonising organic debris and plant roots. Although the actively growing hyphae may be vulnerable to biocides, the sclerotia and melanised hyphae may not. The pathogens *C. coccodes* and *V. dahliae* also survive as sclerotia and *H. solani* as melanised spores and *S. subterranea* as cystsori and may be also be less vulnerable to ITCs. More research is needed to determine the effect of ITCs on the dormant forms of these pathogens in soil.

#### *Brassica species as hosts of potato pathogens*

*Brassica* can host some potato pathogens, thereby helping to maintain or increase their numbers in soil prior to cropping potatoes. The potato strain of *Rhizoctonia solani* (AG3), for example, actively colonised *Brassica* roots in our field plots producing abundant sclerotia. The fungus lived as an epiphyte on the *Brassica* root system. *Brassica* are also good hosts of the root knot (*Meloidogyne* spp.) and root lesion nematodes (*Pratylenchus* spp.). Although *Pratylenchus* is sensitive to some of the ITC's produced by *Brassica* *in vitro* (Potter *et al.* 1998), some *Brassica* species are more resistant to attack by the nematode than others, depending on which ITC's are present in the roots (Potter *et al.* 1999). Ploughed-in green manures are readily colonised by the *Pythium* fungus. In trials in vineyards, ploughing-in *Brassica* green manures increased the number of propagules of *Pythium* in soil. Others have reported *Pythium* to be particularly resistant to ITCs.

There is anecdotal evidence that growing *Brassica* before potatoes reduces the quality of the tubers. Field officers for McCain Foods have noticed that potatoes grown after *Brassica* are 'rougher', being of poorer quality than those grown after pasture for instance. *Brassica* crops may possibly have a detrimental effect on soil structure and nutrients, or may in fact increase populations of some pathogens that affect tuber quality, such as *R. solani*.

#### *Brassica as green manure crops*

Whilst the focus with *Brassica* has been on disease suppression from ITC's, ploughing-in green manures crop can cause disease suppression in other ways. The decay of large amounts of organic material high in nitrogen can release various acids as part of the nitrogen cycle which are toxic to plant pathogens in high concentrations. This process depends on the soil

temperature, moisture and pH. Green manuring can also encourage populations of soil micro-organisms that suppress pathogen activity through competition.

### *The future of biofumigation*

*Brassica* are economically important crops, even in potato production. Their impact on pathogens, disease and yield, as break crops, green manures or biofumigants, whether positive or negative, deserves a more thorough investigation. Current research on biofumigants is focused on determining the ITC profiles of the different *Brassica* species and varieties and on the relative toxicities of these chemicals and their behaviour in the soil profile. These studies can help select varieties with high biofumigation potential. Field studies should include measurements of biomass, ITC concentrations in soil after incorporation, effects on incorporation on soil nutrients and microbial populations and effects on pathogen populations, as well as assessments of disease and yield.

## **3.4 Weed Management in Rotations**

Weed control is critical to the effective management of soil-borne diseases in rotations. Many pathogens have alternative hosts that may include many species of common weeds. Research on rotations in cereal cropping has shown that controlling weeds in crops and pastures preceding wheat can have a significant effect on level of diseases in the wheat crop. This principle applies to potato cropping and there have been some reports indicating that weed control in the crop preceding potatoes has reduced the incidence of damage by *Rhizoctonia*.

Potato plants are easily overlooked as 'weeds'. Significant numbers of volunteer potato plants can emerge after 5 or more years of pasture break between potato crops. These plants act as reservoirs for potato pathogens in the pasture phase. Effective weed control must be a vital component of good rotational practice

## **3.5 The influence of rotation on the major soil-borne diseases of potatoes**

### **3.5.1 Rhizoctonia Canker & Black Scurf (*Rhizoctonia solani*)**

Rhizoctonia canker and black scurf, caused by the fungus *Rhizoctonia solani*, is widespread and common in Australia and can affect emergence, plant growth and tuber yield and quality.

#### **Life-cycle**

*Rhizoctonia* is a versatile soil-inhabiting fungus adapted to survival under a diverse range of conditions, affecting a wide range of crop species world-wide (Anderson 1982; Ogoshi 1987). The fungus can be found in native vegetation as well as in agricultural production areas (Cother 1979; Ogoshi A 1987). It survives in soil as sclerotia (red/black thick walled structures – 'black scurf' on potato skins), as thick walled hyphae (fungal threads) in soil and on tubers or in plant debris (Papavizas *et al.* 1975). Under favourable conditions, the fungus grows actively in soil, colonising the roots of potatoes and other plants. The fungus can colonise roots and stems of many plants without causing disease, thereby maintaining its population. It can survive in organic matter in the absence of hosts. The sclerotia develop on

the surface of tubers when potato plants begin to senesce. Chemicals leaching from maturing tubers signal the fungus to 'shut-down' for the season (Dijst 1990).

### Anastomosis Groups

*Rhizoctonia* has a wide host range and is capable of infecting or colonising many different species of crops and weeds from many different plant families (Adams 1988; Anderson 1982; Ogoishi 1987). The fungus is divided into 13 subspecific groups called Anastomosis Groups (AGs) (Carling *et al.* 2002; 1991) based on somatic (vegetative) incompatibility responses between hyphae of genetically distinct isolates (anastomosis reactions) (Carling *et al.* 1988). Each of these groups has different degrees of specialisation to specific families of plants. Some have a high degree of host specificity. AG3, for example, is most commonly isolated from potatoes and AG8 from cereal roots (Banville *et al.* 1996).

Of the 13 anastomosis groups of *R. solani*, six have been associated with potatoes. They include AG1, AG2 (subgroups 2-1 and 2-2), AG3, AG4, AG5 and AG9 (Banville *et al.* 1996). Traditionally, AG3 has been known as the potato attacking strain, being host-specific to potatoes. However, AG4 and AG5 are also capable of damaging potato plants. Most of the sclerotia isolated from potato tubers are reported to belong to AG3 (Banville *et al.* 1996).

#### *Anastomosis groups of Rhizoctonia in potatoes in Australia*

In the only reported study of *R. solani* in potatoes in Australia, Balali *et al.* (1995) collected isolates of the fungus from stems, roots, tubers and soil in potato crops grown in Virginia and Lenswood in South Australia. Of 301 isolates tested, 90% were AG3 and 7% and 2% were AG4 and AG5, respectively. AG-3 and 5 caused stem and root cankers and black scurf. AG-4 caused stem cankers, severe root cankers and significantly reduced the number and volume of fine roots (feeder roots) but did not produce black scurf (Balali *et al.* 1995).

In Australia, AG-8 is common in cereal production areas and causes severe root rot of cereals and other field crops (Mazzola *et al.* 1996). Potatoes are now grown in traditional wheat cropping areas and glasshouse studies have shown that AG-8 can also cause stem and root cankers and a significant reduction in the number of fine roots of potato plants, but does not produce black scurf on potato tubers (Balali *et al.* 1995).

In a study of potato crops in two districts of Victoria as part of this project, we found not only AG3, 4 and 5, but also AG2 (subgroups AG2-1 and AG2-2). The AG2 groups are often associated with Crucifers (*Brassica*) and Legumes, as well as many other crops (Table 6). The AG3s were the most common, accounting for more than 60% of the isolates of the fungus, whilst the AG2s accounted for about 25%. The AG2s proved to be very pathogenic to potatoes as well as different *Brassica* species and red clover. This is the first report of AG2 causing significant damage to potatoes. It may be that the Australian strains differ to those found elsewhere. The AG2 group was found in clovers in Western Australia and proved to be very pathogenic to this legume (Wong and Sivasithamparam 1985).

*R. solani* AG2s were also implicated as the cause of a new disease in Victorian potato crops described in Section 4.4.3. Symptoms were large patches of wilting plants in relatively mature crops (post-flowering). Fatten and clover seedlings in the patches were also affected by the wilt. This disease has not been described elsewhere and may be due to strains of AG2-1 and AG2-2 that are pathogenic at high temperatures.

In our rotation trials, we found that *R. solani* AG3, the 'potato strain' was able to grow and reproduce on the roots of *Brassica* species and clover forming an epiphytic relationship with its hosts (Section 4.4). This demonstrates that, although *R. solani* AG3 is a potato pathogen, it is able to develop non-parasitic relationships with other crop species as described by Carling *et al.* (1986). The AG2s strains were also common on the roots of *Brassica* and clover. This has obvious implications for the management of rotations.

**Table 6 The relationship between *Rhizoctonia* groups found in potatoes in Australia and different crop species**

Rhizoctonia group and common hosts	Potatoes	Brassicas (Fodder rape, Indian mustard)	Red Clover	Perennial Ryegrass
AG3 Potatoes	Stem & stolon canker Abundant sclerotia on tubers	Sclerotia on roots	Sclerotia on roots	Unknown
AG2 Crucifers, legumes, sugar beet, fathen, clover	Stem & stolon canker Occasional sclerotia on tubers Dry rot of tubers <i>Rhizoctonia</i> wilt	Hypocotyl (lower stem) rot of seedlings & wire stem	Hypocotyl rot & crown rot	Unknown
AG4 Sugar beet, soy bean, peanuts, chickory	Stem & stolon canker Feeder root damage No sclerotia	Hypocotyl rot & wire stem	Unknown	Unknown
AG5 Potatoes	Stem & stolon canker Moderate numbers of sclerotia on tubers	Unknown	Unknown	Unknown

#### *Anastomosis groups and crop rotation*

The relative abundance of AG2s in potato crops in Victoria may be related to the common use of clover-based pastures and the frequent use of fodder *Brassica* after a potato crop. Cropping history can affect the relative abundance of each of the AGs. A study in the USA found that AG-4 and 5 were the most dominant groups in potatoes sampled from fields that did not have a history of potato cropping, whereas AG-3 and 5 were dominant on potatoes taken from fields with a history of potatoes. However, the incidence and severity of *Rhizoctonia* damage was highest in fields with a history of potatoes. AG3 form abundant sclerotia on potato tubers and this will help ensure its dominance in the potato crop because it can also be transmitted on seed potatoes. The incidence of sclerotia from AG2 on tubers is very low (Section 4.4).

#### **The relationship between rotation, the frequency of potato cropping and *Rhizoctonia solani***

There have been many studies on the effects of rotations on *Rhizoctonia* around the world. The results of trials vary considerably because of differences in rotations, soil types, climates, cultivars and cultural practices. The most important factor determining the incidence and severity of damage by the fungus was found to be cropping frequency (Scholte *et al.* 1987, 1992). The greater the frequency of cropping with potatoes in a rotation the greater the

incidence and severity of damage in potato crops. *R. solani* AG-3 dominates in these situations.

The effects of specific crops that precede potatoes or the effect of specific rotational sequences on the fungus and the disease is not clear-cut. *Rhizoctonia* can survive for long periods in soil but debris of various species of plants have different capacities to support the saprophytic survival of the fungus, thereby affecting the population level in soil. For example, in a study in Canada, *R. solani* was isolated more frequently from clovers (preceding potatoes) than any other crop, but the incidence of isolation from winter wheat and ryegrass was also relatively high. On the other hand, the incidence on barley was low. In another study in the US, soil with a 2-year rotation of oat and potato had the lowest saprophytic activity of *Rhizoctonia* and the lowest incidence of disease on stems, roots and tubers compared with rotations involving buckwheat, soybean, corn or peas. In other studies involving 2-year rotations, stem canker was least in potatoes after wheat than after corn, compared with potato-onion or potato barley. However, other researchers have not found clear differences in the incidence of disease between different rotations. The impact of rotation on *R. solani* seems to depend on particular rotation sequences over the long-term rather than the short term. A number of issues relating to *Rhizoctonia solani* in rotations is discussed in more detail in Section 4.1, 4.2.3 and 4.4.

There is some evidence that the effects of rotation on *Rhizoctonia* depend on the potato cultivar. One study reported that potato-oats-soybean and potato-oats-millet would provide the best long-term rotation for Russet Burbank, whereas potato-oat appeared to be best suited to cv. Kennebec and cv. Katahdin in reference to control of *Rhizoctonia*.

## Managing rotations to control *Rhizoctonia*

Managing rotations to minimise the damage caused by *R. solani* will need to take into account a number of issues. These include:

- The different strains of the fungus present, their relative abundance and importance in the disease cycle;
  - Other hosts of the fungus - plant species in which the fungus can grow and multiply (e.g. *Brassica*);
  - Plant species that the fungus does not particularly like to colonise. This includes the living plant or debris of the plant species in soil (e.g. oats are said to be a poor substrate for *R. solani* and buckwheat a good substrate);
  - Practices that favour the breakdown of organic debris in which the fungus survives in between potato crops.

*Rhizoctonia solani* survives in crop debris. Sclerotia and larger fragments of crop debris will be more infective than smaller fragments of debris. The viability of the fungus decreases as the debris decomposes into older and smaller fragments. Cultural practices that reduce the size of organic debris in soil can reduce populations of *R. solani*. This includes the timing of herbicide applications or cultivation to kill grasses and legumes in pastures prior to cropping potatoes. Studies in Australia and elsewhere found that a fallow period between pasture and sowing wheat significantly reduced the severity of damage by *R. solani* AG8. In studies elsewhere, the timing of weed control affected the population of *R. solani* in bean crops and delaying herbicide applications until close to crop emergence increased the severity of damping off of pepper and tomato seedlings caused by the fungus.

Long-term pastures are an important component of rotations for potato cropping in many production areas. They are particularly important for seed growers who must practice long rotations. Our work shows that clover can host both *R. solani* AG3 and AG2. Managing the fungus may require the management of clovers in the pasture sometime before cropping potatoes (e.g. removal with selective herbicides), as well as managing organic debris through early cultivation of the pasture. A lot more needs to be learnt about the behaviour and population of the two strains of *R. solani* over the rotation cycle.

### 3.5.2 Powdery Scab (*Spongospora subterranea*)

*Spongospora* is an obligate parasite. This means it needs a live host to multiply and complete its life-cycle. The fungus survives in soil as clumps of spores called cystosori (spore balls) which are relatively resistant to desiccation. Research in Victoria has shown that the spores can be viable after four years in soil (R. F de Boer, unpublished) and circumstantial evidence suggests as long as 18 years.

There are two stages in the life cycle of this fungus. Individual spores in cystosori germinate under cool, wet conditions, probably stimulated by chemicals leaching from potato roots, and produce swimming spores (zoospores). They infect the fine hairs on the surface of potato roots. The fungus multiplies in the root hairs producing another crop of zoospores and the cycle can be repeated in fresh root hairs. This process allows a rapid multiplication of the fungus before tubers are initiated. However, the zoospores are unlikely to survive in soil for long (days or weeks) and may not have an important role in the survival of this fungus in the long-term. In the second stage of the life cycle, a different process of multiplication occurs in infected roots and tubers resulting in the development of survival spores (cystosori) in root galls (seen as white galls or nodules on roots) and powdery scab pustules.

Research has shown that *Spongospora* is able to infect the roots of a very wide range of plant species in glasshouse tests. A host list includes tomatoes, Solanaceous weeds, grasses, cereals, various clovers and fodder *Brassica*. However, it is important to note that only the first stage of the life cycle described above, the production of zoospores, occurs in these plants. Some plant species are more susceptible than others. Generally, the severity of infection is greater in Solanaceous species (eg. tomato and nightshade) than in the roots of grasses and cereals. In some experiments, high levels of infection were recorded on the roots of white clover. The degree of infection may vary with the overall age of the roots. The fungus prefers young roots. It may be possible to use this first stage infection cycle to trap the fungal spores into germinating and infecting a 'trap crop' thereby reducing overall inoculum in the soil prior to planting potatoes. This aspect is being investigated in the UK.

Survival spores (cystosori) of *S. subterranea* are rarely produced in host species other than potatoes. Galls containing cystosori have been found on the roots of deadly nightshade plants in a field in Tasmania and also on the roots of tomatoes in greenhouses in France. This probably only occurs in situations of extremely high disease pressure (ie. high levels of inoculum and prolonged periods of cool temperatures, wet soil and high pH).

Experience shows that the frequent cropping with potatoes increases populations of *Spongospora* in soil. Generally, the incidence and severity of powdery scab did not vary significantly with rotation treatments in the field trials reported here and elsewhere (de Boer and Theodore 1997). This may be because of the longevity of the powdery scab cystosori. A study of the soil population of *S. subterranea* in rotation cycles will be beneficial and

appropriate tools are currently being developed (Horticulture Australia Project PT01019). Because of its ability to persist in soil for many years, the use of resistant cultivars is an important consideration in the management of powdery scab.

Powdery scab is sensitive to soil pH, temperature and water content. There is anecdotal evidence of a higher risk of powdery scab in potatoes cropped after improved pastures (clover/grass pastures that have been limed) than in potatoes after grass pasture. Adding lime to soil can increase the risk of powdery scab. Rotations that affect soil structure, thereby reducing drainage, may favour powdery scab. Incorporation of large amounts of green manure crops into soil prior to potatoes could potentially increase powdery scab, if this results in increased soil moisture levels or reduced drainage.

### 3.5.3 Silver Scurf (*Helminthosporium solani*)

Silver scurf is one of the most common diseases of potato tubers around the world and the most common disease of seed potatoes in Australia (de Boer and Wicks 1994). The fungus only attacks the potato skin, affecting tuber quality but generally not yield. Until recently, it was believed that *H. solani* did not survive more than a few months in soil and was mainly perpetuated through the planting of infected seed potatoes. However, recent work in Victoria shows that the fungus is soil-borne and widespread in traditional potato cropping districts. When disease-free mini-tubers (produced in a glasshouse) were planted after 8 years of pasture, 100% of their progeny were affected with silver scurf, indicating that inoculum of *H. solani* was soil-borne. Evidence from other trials in Victoria suggests that the fungus may also occur in virgin soil.

For a disease as common as silver scurf, surprisingly little is known about the ecology of the fungus and how it survives in soil. *H. solani* is not known to have any other hosts. It does not grow on the roots of potato plants. A study in the USA found that the fungus can multiply on the roots of dead grasses (Merida and Loria 1994) which suggests that it may have some activity as a saprophyte in soil. Volunteer potatoes probably play an important role in the survival of this pathogen in the period between potato crops.

The disease was common in rotation field trials in Victoria and South Australia, but no major differences were recorded between different rotation treatments. Both seed and soil-borne inoculum contribute to disease in the potato crop. Evidence from field trials with chemical treatments shows that seed-borne inoculum contributes to the disease in progeny, more so when planted in virgin soil, than in production areas with a history of potato production (de Boer 1997). *H. solani* is an enigma. It is clear that the fungus survives in Australian soil for several years or more. However, much more needs to be learnt about how the fungus survives without its potato host and whether it utilises other species, such as grasses, in the rotation.

### 3.5.4 Black Dot (*Colletotrichum coccodes*)

Black dot fungus commonly attacks potatoes and tomatoes. It is common and widespread in Australia as a tuber blemish disease (de Boer and Wicks 1994). The disease proved to be very common in rotation trials in Victoria and South Australia and in commercial crops that were surveyed in Victoria as part of this project. Black dot gets its name from the abundant small, dot-like black sclerotia that are commonly found on senescent and dead potato roots, stolons and stems below and above the ground, as well as on tubers (Dillard 1992). The fungus

progressively colonises the roots, stems, stolons and tubers of potato plants as the crop develops. Severely affected plants can wilt under stress, although, generally, the fungus does not cause serious damage to potatoes (Harrison 1963).

Very little is known about the ecology of this fungus in Australia. It is reported to survive in soil for up to 8 years as sclerotia in crop debris (Dillard and Cobb 1998). Studies in the USA found the number of propagules of *C. coccodes* in soil to be related to the history of potato cropping (Barkdoll and Davis 1992). **The fungus was common in ground with a history of potatoes but undetectable in virgin ground.** In Victoria, the disease was relatively common in potatoes grown after 8 years of pasture in a study where disease-free minitubers were planted as seed (de Boer 1997). The fungus can colonise roots and stems of many plant species besides potato and tomato and these hosts may also play an important role in its survival in the period between potato crops (Raid and Pennypacker 1987). Weed hosts include the nightshades, shepherds purse and fother.

In trials conducted in Victoria and South Australia, the incidence and severity of black dot did not vary significantly with rotation. The number of propagules of *C. coccodes* in soil at Langhorne Creek and Woodside in South Australia did not correlate well with disease incidence on tubers at harvest. Surveys of Russet Burbank crops in Victoria did not find a relationship between the duration of the break from potatoes (1-2 years or 5-6 years). Our experience suggests that disease on the seed piece plays an major role in the disease epidemiology confounding any effects of cropping history and rotation. The challenge is to break the cycle. This will require an understanding of the relative importance of seed verses soil-borne inoculum, the survival of *C. coccodes* in Australian soils and the relationship between the fungus and other crop species in rotations, particularly pasture species. The ability of the fungus to survive for several years in a dormant state in soil makes it a particularly difficult candidate for management.

### 3.5.5 Common Scab (*Streptomyces* spp.)

Common scab is caused by an unusual bacteria-like microorganism belonging to a group called the Actinomycetes. Most representatives of this group are involved in the rotting down of organic matter. The disease has been a persistent problem for Russet Burbank producers on the north coast of Tasmania and more recently in seed and processing production areas of southern Victoria.

There are a wide range of disease symptoms, associated with a number species of *Streptomyces*, namely common scab (*S. scabies*; neutral to alkaline soils), acid scab (*S. acidiscabies*; soils with pH 5.5 or less), American russet scab (*S. aureofaciens*) and European russet (or netted) scab (*Streptomyces* spp.). Common scab has become more prominent with changes in varieties and increased production in new soil types and climates in Australia. The acid tolerant strains of *Streptomyces* have recently been identified in Australia.

*Streptomyces* survives in decaying organic matter and possibly on the roots of living plants. The life cycle of this organism, the strains affecting potatoes, and the factors that govern its activity and survival in soils in Australia are not well understood. **The pathogen can be spread by planting infected seed. However, circumstantial evidence suggests that the strains that attack potato are also present in 'virgin' soil.** *Streptomyces* is common in heavily manured areas around dairies or in fields heavily manured with animal wastes. Organic matter is a

good food base for the bacteria. Recent experience with the disease in Victoria suggests that populations of *Streptomyces* may explode within a season.

A relatively low incidence of common scab was recorded in some years in the rotation trials in South Australia, but not in Victoria. Because the organism survives in organic matter as a bacteria it may be more prone to changes in its environment than powdery scab, for instance. Thus changes in substrate (crops species) and the soil environment (soil chemistry, pH, temperature, moisture), relating to rotation and cropping practices such as green manuring, will potentially affect the population of *Streptomyces*.

Hosts of *Streptomyces*, other than potatoes, include a range of root crops such as red and sugar beet, carrot, parsnip, radish, rutabaga and turnip. It is possible that the organism may live on the roots of many other living plants. Ransom *et al.* (1994) reviewed the published literature on the effects of rotation on common scab for Horticulture Australia. The main finding was that the greater the frequency of potato cropping in a rotation, the higher the incidence and severity of common scab. There was no clear message regarding the relationship between cropping history, with regards to crop species, and common scab. The results of research around the world are variable and often conflicting. However, some work from the USA indicates that rotations of 3 to 4 years with non-host crops can control populations of *Streptomyces*. Green manure crops, including rye, millet and oat, have been reported to reduce the incidence of common scab. Ploughing-in legumes, particularly red clover, is reported to exacerbate common scab in potatoes.

Common scab can be very sensitive to soil pH; the risk of disease is increased by liming for the high pH tolerant *Streptomyces*. On the Tasmanian north coast potatoes are grown in rotation with onion, poppy, brassica or pasture. The practice of liming these crops may increase the risk of common scab in subsequent potato crops. Severe outbreaks of common scab in Russet Burbank potatoes in Victoria have been associated with the application of lime.

Recent research in Canada and Australia has shown a good link between soil populations and disease incidence. Diagnostic tools are being developed which will allow the rapid detection and quantification of the pathogenic strains of *Streptomyces* in soil (PT01019). These tools will be invaluable in studying the populations of the organism in pastures and in different crop rotations.

### 3.5.6 *Verticillium* Wilt (*Verticillium dahliae*)

*Verticillium* wilt was for many decades not considered to be an economic disease of potatoes in Australia, although it causes significant losses overseas. *Verticillium* infects roots and stems and inhabits the vascular system of plants causing early senescence of stems or whole plants. The fungus also is part of a complex of pathogens, including the nematode *Pratylenchus penetrans* (root lesion nematode), associated with 'early dying' of potatoes in North America. The early dying syndrome is becoming common in Russet Burbank crops in parts of South Australia and New South Wales. The association between the nematode and the fungus is not clear. Plants damaged by nematode may be more susceptible to damage by the fungus.

*Verticillium dahliae* is the most common of the two species of *Verticillium* (the other is *V. albo-atrum*) affecting potato crops in Australia. The fungus can survive in soil as

microsclerotia, either free or embedded in plant debris. *V. albo-atrum* can be transmitted on seed potatoes, but the risk is low with *V. dahliae*. The fungus has a wide host range and can also survive at low levels on the roots of many symptomless (without causing disease) crops and weeds. Although grasses and other monocots are generally not considered to be good hosts of *Verticillium*, there is evidence that the fungus can systematically colonise barley, wheat and oats. The fungus infects over 50 species of plants covering 23 families. Common weeds suspected as hosts include Solanaceous weeds (eg. nightshade), fother (Chenopodium album), shepherds purse (*Capsella bursa-pastoris*) and dandelions (*Taraxacum* spp.).

Frequent cropping of potatoes maintains high populations of *Verticillium* in soil. However, the effectiveness of rotations in controlling the disease depends on the initial population densities. Many studies overseas have shown that various rotation practices can affect populations of this fungus. However, it has proven difficult to reduce population levels below the thresholds at which economic damage occurs. Microsclerotia are very persistent in soil and some studies suggest that it may take 5 to 10 years to reduce populations to moderate levels using rotations with grain crops. Generally, long rotations with grasses and legumes are least favourable to *Verticillium*. It is imperative in Australia to avoid rotations that increase populations of this fungus. The spread of potato cropping into the warm, semi-arid regions with sandy soil may see an increase in incidence of damage by *V. dahliae* and nematodes.

Populations of *V. dahliae* were measured over the duration of two rotation trials at Langhorne Creek and Woodside in South Australia. Trends in populations varied over time and between treatments, and the trends differed between the two trial sites. Symptoms of early dying did not feature prominently in the trials. Further research is needed in Australia to determine economic thresholds of this fungus in potato crops and to understand the relationship between the fungus and the nematode *Pratylenus crenatus* was the most common species found in our trial plots. More research is needed on the relationship between the fungus and the nematode.

### 3.5.7 Nematodes

Nematodes have generally not been considered to be serious pests of potato production in Australia, except in some localised problems in some seasons. The discovery of the potato cyst nematode in Australia in recent years has highlighted the potentially destructive nature of nematode pathogens to potato cropping. It is likely that damage caused by nematodes in potato cropping in Australia has probably been underestimated.

Generally, nematodes cause areas of poor growth in crops. Affected plants are less vigorous, turn yellow and stop growing. Nematodes often occur in association with other pathogens such as *Verticillium* and *Rhizoctonia*.

Root knot nematode and root lesion nematode occur in some cropping areas in Australia (Table 7). The root lesion nematode is implicated as one of the causes of the early dying syndrome in Russet Burbank potatoes. Damage caused by these nematodes is likely to become more common in potatoes produced under irrigation in sandy soils in warm semi-arid regions (eg. Riverina, Mallee and Murray River areas) since they prefer coarse textured soils and warm temperatures.

The root knot and root lesion nematodes survive as eggs in soil and in host tissue. Both nematodes have a very wide host range, attacking most major crop plants and a wide range of

weed species. Frequent cropping of potatoes and other hosts can rapidly build-up populations of nematodes. Disease control through rotation is difficult. Grasses in rotations have been used to successfully control some species of the root knot nematode. Populations of *Meloidogyne* (root knot nematode) decline rapidly in the absence of a suitable host. The effectiveness of rotations on the root knot nematode depends on the particular species of nematode. Control of *Pratylenchus*, however, has not been effective because of the very wide host range of this nematode. The survival of *Pratylenchus* is favoured particularly by cereal grain crops, such as barley (*Hordeum vulgare*) and rye (*Secale cereale*).

Although the potato cyst nematode is restricted to a small number of farms in Australia at present, which are quarantined, there is a risk that outbreaks of the nematode will occur in the future. Rotation is essential in controlling this pathogen. PCN has a relatively narrow host range in comparison with the root knot and root lesion nematodes, including tomato, eggplant and various Solanaceous weeds. However, cysts containing the eggs are very resistant to desiccation and can survive in soil for many years although numbers gradually decline with time in the absence of hosts. Long intervals (5 years or more) with non-host crops between potatoes are required to manage populations below very damaging levels.

**Table 7. Some nematodes associated with potatoes in Australia**

Common name	Scientific name	Symptoms
Root lesion nematode	<i>Pratylenchus penetrans</i> <i>P. coffeae</i> <i>P. crenatus</i> <i>P. neglectus</i> <i>P. thornei</i>	Patches of poor growth in crop - plants are less vigorous, turn yellow and stop growing, small pimples on the tuber skin
Root knot nematode	<i>Meloidogyne</i> spp.	Knots or warts on roots and tubers
Potato cyst nematode (PCN) <sup>†</sup>	<i>Globodera rostochiensis</i>	Stunting and early senescence

<sup>†</sup> Found only on a small number of quarantined farms in Victoria. Eradicated from WA

Nematode numbers in soil under different treatments were recorded in rotation field trials in South Australia. *Pratylenchus crenatus* was the most common nematode found. Very little is known about the impact of this nematode in potato cropping in Australia. Pathogenicity tests and studies of economic thresholds are needed to help understand its importance as a potato pest. Populations of the nematode increased with each consecutive cropping cycle in most treatments at Langhorne Creek with seasonal peaks, but remained relatively constant at Woodside.

### 3.5.8 Rotations as part of Integrated Pest Management Systems

Rotation is a critical component of Integrated Pest Management Systems. Many of the benefits of rotations can be rapidly eroded without other disease management strategies.

#### Hygiene

Many pathogens can be introduced into fields on seed potatoes or on contaminated machinery. Hygiene strategies to minimise the re-contamination of fields with pathogens include:

- the use of certified seed tubers with minimum levels of skin diseases;

- hygiene practices in sheds that minimise the contamination of elite seed stocks with pathogens; and
- disinfection of machinery and work areas to avoid the spread of pathogens in soil adhering to planters, harvesters and grading tables and bins.

### **Resistant cultivars**

The use of resistant or less susceptible cultivars, is one of the most effective strategies for the control of pests and diseases. Breeding and selection must be one of the major long-term aims for effective disease control. Introducing resistant or less susceptible cultivars into rotations have been shown to contribute, not only to a reduction in disease incidence but also to reductions in populations of pathogens in soil. The use of resistant cultivars can also alleviate the need for very long rotations in some cases. For example, in the New Polders in the Netherlands, a yield reduction of 10% in a three-year compared to a six-year rotation could be reduced to about 3% using a cultivar tolerant to *Verticillium dahliae* and to about 8% using a cultivar resistant to netted scab (Lamers *et al.* 1989).

This strategy also applies to crops grown in rotation with potatoes. For example, it would be beneficial to use *Brassica* species with some resistance to the root lesion nematode in a rotation to help minimise nematode populations.

### **Cultural, chemical and biological control**

A range of cultural (nutrition, cultivation, irrigation), chemical and biological management strategies for soil-borne diseases helps reduce the damage done by pathogens in crops but also contributes to reductions in pathogen populations.

Research in the Netherlands has shown that in the long-term, soil fumigation in short rotations is not sustainable and some rotational strategies have resulted in better yields than land frequently subjected to fumigation

### **Weed control**

Many so called 'unspecialised' pathogens (eg. *Rhizoctonia*, *Colletotrichum*, *Verticillium*) have a wide host range and are able to colonise the roots and stems of many different plant species, thereby surviving the period between each potato crop. Weed control, including the control of volunteer potatoes, is essential to the effective use of rotations for disease management.

### **Conclusions**

Research shows that crop rotation is critical to the management of soil-borne diseases of potatoes. Reducing the interval between potato crops in a rotation leads to significant increase in population densities of soil-borne pathogens and pests, and consequently to economically important reductions in yield and quality of potatoes. Adding more nitrogen, organic matter or using other cultural practice does not compensate crop losses caused by increased cropping frequency of potatoes.

The aims of crop rotation, besides providing versatility in sources of income and stabilising income, are to maintain soil structure, organic matter and nutrients and minimise populations of soil-borne pathogens and control weeds. The effectiveness of rotations in reducing

populations of plant pathogens below economic thresholds depends on the life-cycle and mode of survival of each particular organism, choice of crops rotated with host crop and returns of organic matter and nutrients, which stimulate growth of pathogen's antagonists and competitors in soil.

There is scope for manipulating rotations to manage most soil-borne pathogens. However, rotation must be practiced as part of an Integrated Pest Management System. For optimum benefits, rotation must be integrated with hygiene practises on farms, including high quality seed potatoes, the use of resistant or less susceptible cultivars, appropriate cultural, chemical and biological control strategies and effective weed control throughout the rotation sequence.

The challenge is for researchers to provide information on the optimum health standard for seed, appropriate hygiene practices, resistant cultivars, cultural, chemical and biological control strategies, appropriate use of fertilisers, manure crops, methods of cultivation and a sequence of rotations for optimum maintenance of the soil condition and disease management.

## 4 Technical Report: Influence of rotation and biofumigation on soil-borne diseases of potatoes

### 4.1 The relationship between rotation and disease and yield in Russet Burbank potatoes in the Central Highlands Region of Victoria – the results of a survey

#### Summary

A systematic survey of 16 commercial Russet Burbank crops in the Central Highlands region of Victoria did not find a correlation between the duration of a 'break' between potato crops (1-2 years or 5-6 years pasture) and disease and yield. Some of highest levels of disease were recorded in crops with a relatively long break (5-6 years) from potatoes. Stem and stolon canker, caused by *Rhizoctonia solani*, was the most common disease in the growing crop with the incidence of affected plants ranging from 1-76%. Black dot (*Colletotrichum coccodes*) was the most common disease on tubers at harvest time, with the incidence of affected tubers ranging from 0-30%. The highest recorded yield of 64 t/ha was produced in a crop grown after long-term pasture with no prior history of potatoes. In contrast, one of the lowest yields recorded (33 t/ha) was in a crop grown after a relatively long break from potatoes (five years of pasture). This study indicates that there are many other variables, besides cropping history, that affect disease and yield in potatoes.

#### Introduction

Potatoes are traditionally cropped after a pasture phase of two years or more duration in many production areas of Australia. Potato production in these areas is often part of a mixed enterprise involving sheep or cattle (dairy or beef), hence the need for pastures. Other crops such as cereal rye (green manure), fodder *Brassica*, oilseed *Brassica*, Indian mustard (mustard *Brassia*) and various cereals (wheat, winter wheat, oats and barley) are often grown after potatoes before pastures are sown down again. Pastures are often a mixture of grasses and fodder legumes (e.g. clovers) or pure stands of medic and lucerne, for example.

The 'break' between potato crops in a field may be as little as a few months. For example, potato crops are grown one after the other, perhaps with a cereal rye grown as a green manure crop in between potatoes, as is the practice for some growers in the Koo Wee Rup Swamp in Victoria. In the Albany swamps in Western Australia continuous production is interspersed with winter flooding. More commonly, potatoes are cropped once in a rotational cycle, although some growers may grow two or three crops in succession in a cycle. Early generation (G0-G3) seed potatoes can only be grown after a minimum break of five years without potatoes (one year in six to potatoes). The forth and fifth generations of seed (certified seed) is grown on a minimum of a three-year break (one year in four to potatoes). For the most part, the period between potatoes is pasture. A break of five years is considered to be a 'long' rotation and one to two years a 'short' rotation.

Overseas research shows a correlation between the frequency of potato cropping in a rotation, (i.e. the number of potato crops in a cycle), and disease and yield. Generally, the longer the gap between potato crops in a cycle, the lower the incidence and severity of diseases and the greater the yields (Bollen *et al.* 1989).

A systematic survey of commercial crops (cv. Russet Burbank) in the Central Highlands of Victoria was conducted to determine if there was a relationship between the duration of the 'break' period preceding a potato crop and disease and yield in potatoes.

## The Survey

### *Field sites*

The survey was conducted on 16 sites planted to commercial crops of Russet Burbank potatoes during the 1996/97 season in the Central Highlands area of Victoria near Ballarat. Soils were described as ferrosol and kurosol, typical of this area of Victoria, which is an important production centre for potatoes processed for French fries. Crops were chosen with the help of field officers from McCains Foods who have a good knowledge of growers and their practices in this area. The choice of sites was based on the duration of the 'break' period between potato crops in a specific field. These were either 'short' breaks (one-year or two years between potato crops) or long breaks (five or more years) (Table 8).

**Table 8 Cropping history of sites in the Central Highlands of Victoria surveyed for disease and yield prior to cropping potatoes in 1996/97**

<b>The sequence of crops grown prior to the 1996/97 potato crop</b>	<b>No. of fields surveyed for each rotation</b>
5-6 years of pasture	4 paddocks
5-6 years of pasture-potato-barley	4 paddocks
2 years of pasture	4 paddocks
5-6 years of lucerne	2 paddocks
5-6 years of pasture-potato-barley-potato-barley	1 paddock
Pasture with no previous potato crops	1 paddock

### *Sampling, disease and yield assessments*

Potato plants were sampled during early crop growth (8-10 weeks after planting) and at late maturity (18-20 weeks after planting), along the lines described by Leach (1993) and Scholte (1992). Sampling involved digging-up a single plant from every 10<sup>th</sup> to 15<sup>th</sup> row every 50 paces along each row. Totals of 100 and 50 plants were sampled at each site at the early crop growth and late growth stages, respectively.

At the early growth stage, each plant was assessed for severity of stunting and the severity of stem and stolon canker. Plants were assigned ratings of 0, 1, 2 or 3, for unaffected, slightly, moderately or severely stunted, respectively. Severity of stem canker was assessed on the basis of the number of lesions per stem, the severity of lesions and the number of stems affected on each plant. Categories of 0, 1, 2, 3 and 4 were assigned to plants with 0 (no stem canker lesions), less than 25% of stems affected, 25-50% of stems affected, more than 50% stems affected and all stems pruned below ground, respectively. The severity of canker on stolons was recorded using the same scale. Disease incidence was recorded as the proportion of stunted plants, plants with stem canker or plants with stolon canker.

At the late growth stage, plants were assessed for symptoms consistent with damage by *R. solani* in each field as described for the early disease assessment. Senescence was

significantly delayed in these plants such that they remained green and active after most of the surrounding plants had died down (Malformed plants). Typical symptoms included severely shorted leaf stems, aerial tubers in the leaf axils above ground and numerous small tubers clustered around the base of the stem just below ground level.

One tuber from each of the 50 plants sampled at the late growth stage was collected for the assessment of skin blemishing diseases. Tubers were washed under high pressure to remove soil and each tuber examined for the presence of skin diseases. The severity of silver scurf, black dot, powdery scab and common scab on each tuber was rated on a scale of 0-4, based on the proportion of tuber surface affected. Tubers were assigned severity ratings of 0, 1, 2, 3 or 4 for; no disease; up to 2% (trace); 2-10%; 10-25% or more than 25% of tuber surface affected, respectively. Severity of black scurf was rated on a scale of 0-3 where ratings of 0, 1, 2, or 3 were assigned to tubers with; no sclerotia; lightly covered; moderately covered or heavily covered with sclerotia, respectively. Disease incidence was recorded as the proportion of tubers in each sample with a particular disease. The presence of any obvious diseases on foliage, such as target spot (*Alternaria solani*), was also recorded.

#### *Yield Assessments*

Yield data from each field sampled was obtained from individual growers at the end of the season. This data was reasonably accurate since it was usually based on the tonnages weighed-in at the McCain's processing factory.

#### *Weather data*

Meteorological data (minimum and maximum temperatures) for the growing season was obtained from a weather station nearest the survey areas (Ballarat aerodrome, Climate and Consultancy Section in the Victorian Regional Office of the Bureau of Meteorology). The risk of stem canker is generally higher when soil temperatures at emergence are low (10°C or less). The incidence and severity of stem canker at early crop growth was compared against temperature data to determine if there was any relationship between temperature and disease.

#### *Statistical analysis*

All data were analysed by analysis of variance (ANOVA) using Genstat for Windows 5<sup>th</sup> Edition <sup>TM</sup> (Lawes Agricultural Trust, Rothamsted Experimental Station).

#### **Results**

Crop growth (stunting), Rhizoctonia disease and yield parameters for all crops surveyed are presented in Table 9 and averages for each replicate treatment presented in Table 10. Disease caused by *Rhizoctonia solani* was prominent in the potato crops surveyed. At the early crop growth stage, symptoms included lesions (cankers) on the stems and stolons, resulting in the pruning of stems and stolons. Affected plants were often stunted compared with healthy plants. When crops had died down, Rhizoctonia damage was evident as green plants that had not yet senesced and these had shortened internodes, aerial tubers in the leaf axils and clusters of small tubers at the base of the plant ('malformed plants'). The incidence of stunting in the surveyed crops ranged from 1-31% plants affected (average 16%) and the incidence of plants with stem canker from 1-76% plants affected (average 35%) (Table 9 and Table 10). At full maturity, the incidence of plants with aerial tubers varied from 2-16% (average 7%).

The disease was also evident on the tubers as black scurf (sclerotia of *R. solani*) with the incidence of affected tubers varying from 0-38% between the sites surveyed (average 13%) (Table 9 and Table 10). Black dot and powdery scab were also relatively common on tubers (0-30% and 0-34% tubers affected, respectively) (Table 11). On the other hand, the incidence of tubers with silver scurf and common scab was negligible. The highest incidence of black dot recorded was for potato tubers grown after pasture with no previous history of potatoes. Target spot was generally very common, affecting between 2-76% of plants across the 16 sites (Table 11).

Yields varied from 32.1 to 64.2 t/ha, averaging 46 t/ha (Table 9 and Table 10) The lowest yields, 32.1, 33.4 and 37.5 t/ha, were from potatoes sown after 2 years pasture, 5 years pasture and 5 years pasture-potato-barley rotations, respectively. The highest yield of 64.2 t/ha was from potatoes sown after pasture with no history of potato crops.

The disease parameters and crop yields varied considerably between the different sites within the same rotations. There were no statistical differences in the incidence and severity of diseases, or yields between the different rotations (Table 9 and Table 10). The incidence of stunting and the incidence of stem canker were poorly correlated as were the incidence of stem canker and black scurf. There was no clear relationship between temperature data and disease and yield. Although not significant, there was a trend indicating a relationship between the incidence and severity of stem canker and yield ( $R^2 = 0.48$ ). Crops with the lowest yields of 33.4, 32.1 and 37.5 t/ha had a relatively high incidence (52, 50 and 76% plants affected, respectively) and severity of stem canker (severity ratings of 1.28, 1.01 and 1.36, respectively). Conversely, other crops with 57 and 60% plants with stem canker (severity ratings of 1.36 and 1.43, respectively) yielded 44.5 and 42.0 t/ha.

## Discussion

The systematic sampling of commercial potato crops grown in different rotation sequences did not reveal any clear statistical relationships between rotation, disease and yield. The duration of the 'break' between potato production in each field was generally not correlated with disease incidence and severity or yield. A potato crop grown after a long-term pasture with no previous history of potato production produced the highest yield. On the other hand, the lowest recorded yield was from potatoes grown after a relatively long break of five or more years of pasture.

Overseas researchers generally report a correlation between the duration of the break from potatoes in a rotation and disease or yield. Longer breaks result in reduced disease and higher yields (Hoekstra 1981; Bollen *et al.* 1989; Scholte 1992; Gilligan *et al.* 1996). This data is generally from long-term, replicated field trials of up to 15 years duration. The results of our survey suggest that other factors can have a greater influence on disease incidence and severity in potatoes than the length of the break period between potato crops. The fields surveyed covered a range of soil types and microclimates. Crops were planted at different times and other factors such as the quality of pasture, weed control (e.g. self sown potatoes), soil preparation, seed quality and health, pre-emergence and post emergence weed control, nutrition and irrigation would have varied from field to field. The only way to reduce the impact of these confounding factors is to establish long-term field trials where all rotational sequences are compared within the same field. This way, variables such as soil type, climate, methods of seed bed preparation and soil nutrients will be the same across all treatments. Factors such as weed control, the quality of seed potatoes, disease management, nutrition and

irrigation can also be controlled. This allows a more valid comparison of the influence of different rotations on disease and yield.

The survey provided a valuable insight into disease incidence and severity and yields of commercial crops in the Central Highlands of Victoria. Rhizoctonia canker was the most common disease affecting plant growth in the developing crop with as many as 76% of plants affected at one site. Yields recorded in the survey averaged 46 t/ha. A yield of 64 t/ha at one site demonstrates the production potential that could be achieved in this area. On the other hand, the relatively low yields of 32-38 t/ha recorded in other crops demonstrate a significant opportunity for improvement on some farms.

There was a trend linking lower yields with a relatively high incidence and severity of stem canker, although there were examples of relatively high yields from crops with a high incidence of stem canker. This data does not generally support the contention that *R. solani* causes significant yield loss. Weinhold *et al.* (1982) showed that the severity of stem canker can be directly related to a reduction in yield of progeny tubers. This was not supported by Frank (1978) and Hide *et al.* (1989b), who demonstrated the problems of predicting the amount of yield loss from stem canker. It has been suggested that yield is not affected by *R. solani*, even where severe stem canker is present in the growing crop (Small 1943; Small 1945; Van Emden 1966). In 10 years of research in Victorian potato production areas, we have not been able to demonstrate a clear relationship between the incidence and severity of stem canker and the yield of potatoes (R.F. de Boer, unpublished data).

There was no significant correlation between the incidence and severity of stem canker and black scurf on progeny tubers. This is consistent with the results of other field trials in Victoria (R.F. de Boer, unpublished data). This suggests that the factors influencing the infection by stems by *R. solani* may differ to those affecting the development of sclerotia in the mature crop or, alternatively, the strain of the fungus affecting the stems may differ to that producing sclerotia on tubers. This could also relate to the relative importance of seed verses soil-borne inoculum (Gilligan *et al.* 1996; Simons and Gilligan 1997). The nature of the relationship between diseases caused by *R. solani* on different parts of the potato plants is surrounded by controversy (Simons and Gilligan 1997). Most reports indicate a close relationship between the severity of black scurf on the seed tubers at planting and the subsequent development of stem canker (Banville 1989; Gudmestad *et al.* 1978; Read *et al.* 1989). The severity of stem canker in the growing crop has been positively correlated with the subsequent formation of black scurf on progeny tubers (Chand and Logan 1982). However others report that this relationship is not so straight forward finding it more variable (James and McKenzie 1972; Hide *et al.* 1973; Adams and Hide 1980), whereas some have reported no apparent relationship (Bogucka 1983; Hide *et al.* 1989a).

The most common diseases on progeny tubers were black dot, black scurf and powdery scab. This part of Victoria has a long history of powdery scab and previous research indicates that the pathogen survives for at least four years in pastures (de Boer and Theodore 1997). Surveys of seed potatoes and data from field trials has shown that black dot is very common in Russet Burbank potatoes in this part of Victoria (de Boer 1997) indicating significant levels of both soil and seed-borne inoculum. The relatively high incidence of black dot on progeny tubers recorded in this survey are consistent with the findings of surveys of seed and other field trials (de Boer and Wicks 1994; de Boer and Theodore 1997). Little is known about the epidemiology of the disease or its effect on the growing crop.

This survey identifies major differences in yields between individual potato crops. Some growers were producing twice the tonnage per hectare of other growers. Although, rotation practices may account for some of these differences, there are clearly many other factors affecting yield. The challenge is to determine which factors have the greatest impact on disease and yield in this important cropping area.

**Table 9 The relationship between rotation, plant growth (stunting), stem and stolon canker, malformed plants, black scurf and yield of cv. Russet Burbank potatoes in a systematic survey of potato crops in the Central Highlands, 1996/97**

(Cropping history: y, years; p, pasture; pt, potato; b, barley, l, lucerne)

Cropping history	Location	Plant date (days) <sup>a</sup>	Post emergence						Late maturity		Harvest		
			Stunting		Stem Canker		Stolon Canker		Aerial tubers % plants	Malformed plants % plants	Black Scurf		Yield (t/ha)
			% plants	Severity (0-3) <sup>c</sup>	% plants	Severity (0-4) <sup>d</sup>	% plants	Severity (0-4) <sup>d</sup>	% plants	% tubers	Severity (0-4) <sup>e</sup>		
5y p-pt	Clarks Hill	13-15	16.0	0.18	25.0	0.44	16.0	0.38	2.0	4.0	0.0	0.00	46.9
5y p-pt	Spring-bank	22-27	9.0	0.10	40.0	0.74	20.0	0.41	2.0	6.0	24.0	0.48	42.0
5y p-pt	Millbrook	17-22	17.0	0.21	52.0	1.28	39.0	0.94	8.0	8.0	38.0	0.58	33.4
5y p-pt	Bullarook	28	16.0	0.18	20.0	0.27	6.0	0.06	6.0	4.0	6.0	0.06	56.3
2y p-pt	Spring-bank	10	19.0	0.23	50.0	1.01	34.0	0.76	-	-	28.0	0.40	32.1
2y p-pt	Ascot	22-23	6.0	0.08	20.0	0.36	8.0	0.174	2.0	4.0	2.0	0.04	55.1
2y p-pt	Ascot	22-23	18.0	0.21	26.0	0.46	10.0	0.14	2.0	2.0	0.0	0.00	44.5
2y p-pt	Ascot	5-7	31.0	0.44	30.0	0.65	18.0	0.28	10.0	6.0	24.0	0.28	44.5
5y p-pt-b-pt	Clarkes Hill	18-21	22.0	0.27	57.0	1.36	45.0	0.97	12.0	4.0	26.0	0.42	44.5
5y p-pt-b-pt	Clarkes Hill	17-18	12.0	1.40	76.0	1.86	57.0	1.42	4.0	10.0	14.0	0.16	37.5
5y p-pt-b-pt	Clarkes Hill	33-38	20.0	0.23	20.0	0.34	18.0	0.36	6.0	10.0	16.0	0.28	46.9
5y p-pt-b-pt	Newlyn	9	31.0	0.39	23.0	0.47	6.0	0.09	6.0	8.0	2.0	0.02	49.4
5y l	Ascot	3	10.0	0.15	14.0	0.25	4.0	0.08	12.0	16.0	16.0	0.18	44.0
5y l	Ascot	0-6	8.0	0.10	41.0	0.80	24.0	0.47	16.0	18.0	16.0	0.20	54.3
5y p-pt-b-pt-b-	Clarkes Hill	13	22.0	0.25	67.0	1.43	46.0	1.08	8.0	17.0	0.0	0.00	42.0
p <sup>b</sup>	Ascot	14	1.0	0.01	1.0	0.01	0.0	0.00	4.0	6.0	0.0	0.00	64.2

<sup>a</sup> Planting time in days after the earliest planted crop (0 days)<sup>b</sup> Pasture-potato, no previous history of potato production<sup>c</sup> Severity of stunting: 0, no stunting; 3, no sprouts emerged from soil<sup>d</sup> Severity of stem canker: 0, no stem or stolon cankers; 5, all sprouts pruned and no emergence from soil or all stolons pruned<sup>e</sup> Severity of black scurf symptom on tuber: 0, no sclerotia; 4, heavy coverage of large sclerotia on tuber surface

**Table 10 The relationship between rotation, plant growth (stunting), stem and stolon canker, malformed plants, black scurf and yield of cv. Russet Burbank potatoes in a systematic survey of potato crops in the Central Highlands of Victoria 1996/97; averages for each cropping history**

(Rotation/cropping history: y, years; p, pasture; pt, potato; b, barley, l, lucerne)

Cropping history	Replication <sup>A</sup>	Post Emergence						Maturity		Harvest	
		Stunting		Stem canker		Stolon canker		Plants with aerial tubers	Mal-formed plants	Black Scurf	
		% plants	Severity (0-3) <sup>C</sup>	% plants	Severity (0-4) <sup>D</sup>	% plants	Severity (0-4) <sup>D</sup>	% plants	% plants	% tubers	Severity (0-4) <sup>E</sup>
5y p-pt	4	14.5	0.17	34.3	0.68	20.3	0.45	4.5	5.5	17.0	0.28
2y p-pt	4	18.5	0.24	31.5	0.62	17.5	0.34	4.7	4.0	13.5	0.18
5y p-pt-b- pt	4	21.3	0.57	44.0	1.01	31.5	0.71	7.0	8.0	14.5	0.22
5y l-pt	2	9.0	0.13	27.5	0.53	14.0	0.28	14.0	17.0	16.0	0.19
5y p-pt-b- pt-b-pt	1	22.0	0.25	67.0	1.43	46.0	1.08	8.0	20.0	0.0	0.00
p-pt <sup>B</sup>	1	1.0	0.01	1.0	0.01	0.0	0.00	4.0	6.0	0.0	0.00
F test		0.187	-	0.293	0.403	0.396	-	-	-	0.791	0.786
I.s.d. (p=0.05)											
min rep		23.1	-	60.8	1.60	53.3	-	-	-	42.6	0.67
Max-min.		18.3	-	48.0	1.26	42.1	-	-	-	33.7	0.53
max rep		11.6	-	30.4	0.79	26.6	-	-	-	21.3	0.34

<sup>A</sup> No. of replicate fields sampled with this history<sup>B</sup> Pasture-potato, no previous history of potato production<sup>C</sup> Severity of stunting: 0, no stunting; 3, no sprouts emerged from soil<sup>D</sup> Severity of stem canker: 0, no stem or stolon cankers; 5, all sprouts pruned and no emergence from soil or all stolons pruned<sup>E</sup> Severity of black scurf symptom on tuber; 0, no sclerotia; 4, heavy coverage of large sclerotia on tuber surface

**Table 11 The relationship between rotation, target spot on foliage, black dot and powdery scab on progeny tubers and the yield of cv. Russet Burbank potatoes in a systematic survey of potato crops in the Central Highlands of Victoria, 1996/97**

(Cropping history: y, years; p, pasture; pt, potato; b, barley; l, lucerne)

Cropping history	Replication <sup>A</sup>	Target spot % plants	Black dot % tubers	Severity (0-4) <sup>C</sup>	Powdery scab % tubers	Severity (0-4) <sup>C</sup>	Yield (t/ha)
5y p-pt	4	34.0	19.0	0.75	7.5	0.17	44.7
2y p-pt	4	43.3	11.0	0.33	16.0	0.48	44.0
5y p-pt-b-pt	4	45.5	10.0	0.31	12.5	0.27	44.6
5y l-pt	2	63.0	20.0	0.80	12.5	0.20	49.2
5y p-pt-b-pt-b-pt	1	32.0	9.0	0.30	22.0	0.60	41.9
p-pt <sup>B</sup>	1	76.0	29.0	1.10	1.0	0.02	64.2
F test	-		0.519	0.418	0.745	0.621	0.382
I.s.d. (p=0.05)	-						
min rep	-		33.6	1.38	36.9	1.02	25.9
max-min.	-		26.6	1.09	29.1	0.81	20.4
max rep	-		16.8	0.69	18.4	0.51	12.9

<sup>A</sup> No. of replicate fields sampled for each cropping history<sup>B</sup> Pasture-potato, no previous history of potato production<sup>C</sup> Severity of disease on potato skin: 0, no disease; 4, >25% of tuber surface covered

## **4.2 The effects of crop rotation on disease and yield of potatoes**

### **4.2.1 Summary**

Four rotation trials were conducted in Victoria and South Australia in which different crop species (mixed pasture, clover, perennial ryegrass, wheat, oats, barley, buckwheat, cereal rye, different varieties of fodder and mustard seed *Brassica* and white radish) were rotated with potatoes over one to three cycles. In some trials and some seasons, pathogen populations in soil and disease incidence and severity in the crop and on tubers varied with rotation treatments. Similarly, yields varied by up to 30% between some treatments in some seasons. However, there were no consistent patterns linking the type of crop grown prior to potatoes (cereal, *Brassica*, pasture) or particular sequences, with variations in disease and yields. There was no clear evidence showing that the various 'biofumigant' crops (*B. napus*, *B. juncea*, *B. campestris* and *Raphanus*) had a significant impact on disease incidence and severity.

### **4.2.2 Introduction**

The previous study reported the results of a systematic survey of commercial crops to determine if there was a correlation between the duration of the break from potatoes and disease incidence and severity and yields of potatoes. Although there were apparent links between disease and the break period in some crops, overall the survey was unable to show a good correlation between the break period and disease and yield. It was concluded that there were many other factors, apart from the break, which influence disease and yield. Only through replicated field trials can the impact of many of these variables, such as soil, climate, seed source, nutrition, weed management and irrigation be eliminated or managed.

Field trials were conducted in Victoria and South Australia to evaluate the impact of a single crop species grown before potatoes on pathogen populations, disease and yield. The crop species studies included:

- Mixed pasture - perennial ryegrass and fodder legumes
- Individual components of pasture – perennial ryegrass and clover
- Cereals – wheat, barely, oats and cereal rye
- Novel crops - buckwheat
- Various Cruciferae with different levels of 'biofumigation potential' – fodder rape (*Brassica napus*), Indian mustard (*B. juncea*), the condiment '*Brassica*' white radish (*Raphanus sativus*) mixtures of *Brassica* (*B. napus* and *B. campestris*).

### **4.2.3 Rotation trials in the Central Highlands region of Victoria**

#### **Materials and Methods**

##### *Experimental site*

Two field experiments were conducted at the Central Highlands Integrated Production Systems (CHIPS) Demonstration Farm, Bullarook, near Ballarat in the Central Highlands

area of Victoria. Soil type is described as a ferrosol (1996), which is a volcanic clay-loam soil (pH 5.5-5.8 in H<sub>2</sub>O, 4.7-5.0 in CaCl<sub>2</sub>) with an organic matter content ranging from 5 to 10%. The demonstration farm is on a rotation of pasture (predominantly perennial ryegrass and clovers) and potato, with potatoes sown every fourth or fifth year.

### *Experimental treatments and design*

#### **Rotation Trial 1**

On the 26 November 1996, seed of perennial ryegrass, red clover, fodder rape or buckwheat was drilled into experimental plots on a site previously in long-term (5 years) pasture. The history of this site is presented in Table 12 and details of crops are presented in Table 13. The plots were within a field that had been cultivated in late winter and early spring in preparation for potato planting in late spring. Experimental treatments (prior to potatoes) were arranged in randomised Latin Square of 4x4 plus two randomised columns, making 24 plots altogether. All treatments were replicated six times. Plots were 4.87m wide (six potato rows) and 11m long, with a row spacing of 0.81m and a plant spacing of 0.36m along the row. All plots were cultivated with mould-board plough on 26 August 1997 and power harrowed on the 18 November 1997, one week before planting potatoes.

Experimental plots were fertilised and planted on 26 November 1997 with whole seed tubers of commercial certified seed of cv. Russet Burbank in one pass with a custom-made two-row plot-planter. The fertiliser was banded to either side of the seed setts along the rows (1000 kg/ha Pivot™ fertiliser; triple supersphosphate, ammonium sulphate, potassium chloride; NPK 14:10:14, 12% sulphur). Seed tubers had been dusted with tolclofos-methyl (Rizolex 100D®, 2kg/tonne) prior to planting to minimise carry-over of seed-borne *Rhizoctonia solani*. Crop management (weed management, irrigation and fungicide sprays) was as for a commercial Russet Burbank crop. Plots were side-dressed with single superphosphate at 50 kg/ha (11% sulphur, 22% calcium) on 11 February 1998.

**Table 12 Rotation Trial 1, Bullarook, Victoria – Cropping history and rotation sequence**

<b>1991-1996</b>	<b>1996/97</b>	<b>1997/98</b>
Pasture	Perennial ryegrass	Potato
Pasture	Red clover	Potato
Pasture	Fodder Rape 'Hobson'	Potato
Pasture	Buckwheat	Potato

#### **Rotation Trial 2**

A second trial was established adjacent to Trial 1 in the autumn of 1997. This site had the same soil type and cropping history as Trial 1 and was sown to commercial crop of Russet Burbank potatoes during the 1996/97 season. Plots were rotary hoed in late May 1997 and sown to perennial ryegrass, winter wheat, 'Hobson' fodder rape or red clover as outlined in Table 13 and Table 14. On 30 October, 'Hobson' rape and the red clover plots were resown because of poor germination from the Autumn sowing. On 26 May 1998, perennial ryegrass plots were direct drilled to fodder brassica 'BQ Mulch®' or 'Nemfix®' Indian mustard, and the winter wheat plots to 'Striker' fodder rape approximately 3 weeks after all plots had been treated with Roundup® herbicide (glyphosate) (Table 13 and Table 14). The experiment was

design as complete randomised block of six treatments with six replicates. On the 2 December 1998 all plots were planted with whole seed potatoes (commercial certified seed) of cv. Russet Burbank as described for Trial 1. Plots were fertilised in the same pass as sowing seed (Pivot fertiliser (NPK 100:150:100 kg/ha). Seed potatoes had been treated with Monceren® 250 FS fungicide (600g/tonne) to minimise the carry-over of *R. solani*. Plots were irrigated as required with solid set sprinklers. Weed and disease management were as for a commercial crop.

**Table 13 Details of crops sown before potatoes in Rotation Trials 1 and 2**

Crop before potatoes	Sowing rate (kg/ha)	Date of sowing
<i>Trial 1</i>		
Perennial Ryegrass ( <i>Lolium perenne</i> L.) cv. Cordia	15	29.11.1996
Red Clover ( <i>Trifolium pratense</i> L.) cv. Hamna	6	29.11.1996
Fodder rape ( <i>Brassica napus</i> L.) cv. Hobson	3	29.11.1996
Buckwheat ( <i>Fagopyrum esculentum</i> Moench.) cv. Manor	40	29.11.1996
<i>Trial 2</i>		
Perennial Ryegrass ( <i>Lolium perenne</i> L.) cv. Ellett	18	02.06.1997
Red Clover ( <i>Trifolium pratense</i> L.) cv. Cowgrass	9	02.06.1997/30.10.97 <sup>A</sup>
Wheat ( <i>Triticum aestivum</i> L.) cv. Temora	90	02.06.1997
Fodder rape ( <i>Brassica napus</i> L.) cv. Hobson	3	02.06.1997/30.10.97 <sup>A</sup>
Fodder rape ( <i>Brassica napus</i> L.) cv. Striker	3	02.06.1997
'Biofumigation' brassica ( <i>Brassica napus</i> L., <i>Brassica campestris</i> L.) cv. BQ Mulch®	10	26.05.1997
Indian Mustard ( <i>Brassica juncea</i> (L.) Czern.) cv. Nemfix®	6	26.05.1997

<sup>A</sup>Resown at a later date because of poor emergence at the first sowing

**Table 14 Rotation Trial 2, Bullarook, Victoria – cropping history and rotation sequence**

1991-1996	1996/97	Autumn 1997	Autumn 1998	1998/99
Pasture	Potato	Perennial ryegrass	Perennial ryegrass	Potato
Pasture	Potato	Perennial ryegrass	Fodder rape 'BQ Mulch™'	Potato
Pasture	Potato	Perennial ryegrass	Indian mustard 'Nemfix™'	Potato
Pasture	Potato	Winter Wheat	Fodder rape 'Striker'	Potato
Pasture	Potato	Fodder rape 'Hobson' <sup>A</sup>	Fodder rape 'Hobson'	Potato
Pasture	Potato	Red clover <sup>A</sup>	Red clover	Potato

<sup>A</sup>Poor germination resulted in plots being effectively fallow until they were resown in October 1997

#### *Plant growth, disease and yield assessments in potatoes*

In each trial, potato plants in the four middle rows of each plot were counted to determine plant emergence. Each plant was also scored for the degree of stunting using a scale of 0-3 where plants with no stunting, slight, moderate and severe stunting were assigned ratings of 0, 1, 2 and 3, respectively. A total of eight plants were sampled from the 2<sup>nd</sup> and 5<sup>th</sup> row of each plot and assessed for the severity of stem and stolon canker symptoms. Plants were assigned ratings of 0, 1, 2, 3 and 4 when they had no symptoms of Rhizoctonia damage, less than 25%, 25-50%, greater than 50% and all sprouts and stems pruned (no emergence), respectively. At the late maturity, the proportion of plants in the four middle rows of each

plot with symptoms of Rhizoctonia damage (late maturing, shortened internodes and aerial tubers in the leaf axils) was recorded from the middle four rows. Disease incidence in each case was recorded as the percentage of plants with disease symptoms.

The biomass of crops preceding potatoes in Trial 2, expressed as dry matter, was determined in October 1998 prior to preparing the seedbed for potatoes. Plant crowns and foliage were removed from a random 20x20 cm square in each plot, the number of plants were counted and each sample weighed after drying at 70°C to constant weight.

Potatoes were harvested from a 10m length of row from the centre two rows of plots in Trial 1 and 2 on 30 April 1998 and 22 April 1999 respectively. A sub sample of 50 tubers was taken at random from the harvested rows in each plot for tuber disease assessments. The remaining tubers were sorted into weight categories of less than 75g, 75-280g, 280-450g, greater than 450g and misshapen, and the numbers and weights for each category recorded.

The sub-samples of 50 tubers from each plot were washed and each tuber visually inspected for skin diseases and rots. The severity of silver scurf, black dot, powdery scab and common scab on each tuber was scored on a scale of 0-4, where ratings of 0, 1, 2, 3 and 4 were assigned to tubers with no disease, less than 2%, 2-10%, 10-25% and greater than 25% of the tuber surface covered with a symptom, respectively. The severity of the black scurf symptom (*Rhizoctonia solani*) was rated on a scale of 0-3 where tubers with no sclerotia, light moderate or heavy coverage of sclerotia were assigned ratings of 0, 1, 2, and 3, respectively. Disease incidence was recorded as the proportion of tubers in each sample with a particular disease.

### *Statistical Analysis*

The results were analysed by REML Variance Component Analysis for Trial 1 data (Row/column design) and a General Analysis of Variance (ANOVA) for data from Trial 2. Genstat for Windows 5<sup>th</sup> Edition ™ (Lawes Agricultural Trust, Rothamsted Experimental Station)

## **Results**

### **Rotation Trial 1**

On average, 89% of setts sown emerged and 28.6% of plants had some degree of reduced growth (stunting), although severity was very low (less than 0.6 on a scale of 0-3) (Table 16). Rhizoctonia cankers on stem and stolons were the only obvious symptoms of disease on plants during early crop development with an average 12.9% of plants affected (Table 16). The severity of damage to stems and stolons was low (less than 0.3 on a scale of 0-4). An average of 2.5% of plants had symptoms of Rhizoctonia damage at late maturity. More plants were affected with stem canker in potatoes after buckwheat (20.8%) ( $P \leq 0.05$ ) than in potatoes after clover (6.55%). Otherwise there was no significant effect of rotation treatments on the incidence of stem canker. Overall, plant emergence, the severity of canker and the incidence of plants with Rhizoctonia damage at late maturity did not vary significantly ( $P > 0.05$ ) between the different preceding crops. The incidence of stunting was not correlated with the incidence of Rhizoctonia canker.

Black dot was the most common disease on progeny tubers at harvest, followed silver scurf, black scurf and powdery scab, with an average of 72%, 42%, 2.1% and 1.2% tubers affected, respectively. The incidence of tubers with disease did not vary significantly ( $P>0.05$ ) with cropping sequence (Table 16).

Total and marketable yields averaged 44.8 and 40.9 t/ha, respectively, neither of which varied significantly between treatments ( $P>0.05$ ). When comparing number and yields of tubers in the different size categories, the yield of medium sized tubers, which averaged 35.3 t/ha, did not vary significantly ( $P>0.05$ ) between treatments. However, the yield of larger tubers was higher ( $P\leq0.05$ ) under grass and clover than under fodder rape and buckwheat (Figure 2)

#### Rotation Trial 2

Dry matter on plots prior to ploughing-in for potato planting in the Spring of 1998 ranged from 2.1 to 8.9 t/ha, except for the 'Hobson' fodder rape plots which averaged 25 t/ha (Table 15).

**Table 15 Rotation Trial 2, Bullarook Victoria; dry matter (t/ha) of foliage on plots in early October 1998 prior to ploughing-in before planting potatoes in November 1998**

Crops preceding potatoes <sup>A</sup> Autumn 97-Spring 97	Dry matter (t/ha)
Grass-grass	8.9
Clover-clover	5.5
'Hobson'-'Hobson' <sup>B</sup>	25.1
Grass-'BQ Mulch' <sup>B</sup>	2.9
Grass-'Nemfix' <sup>C</sup>	3.3
Wheat-'Striker' <sup>B</sup>	2.1
<i>F-test</i>	<0.001
I.s.d. ( $P=0.05$ )	4.1

On average, 91.9% of setts sowed emerged (not shown in Table) and 16.9% of plants showed some degree of stunting, although severity of stunting was low (less than 1.0 on a scale of 0-3) (Table 17). An average of 42.7% of plants had evidence of Rhizoctonia cankers at early crop growth with a severity of 1.01 on a scale of 0-4 (Table 17) and 11.0% of plants had symptoms of damage caused by *R. solani* at late maturity. None of these parameters varied significantly ( $P>0.05$ ) with different preceding crops.

As in Trial 1, black dot was the most common disease in progeny tubers at harvest, followed by silver scurf, black scurf and powdery scab (average of 66.7%, 31.5%, 17.0% and 5.5% of tubers affected, respectively) (Table 17). Generally, the incidence and severity of these diseases did not vary significantly ( $P>0.05$ ) with different preceding crops.

Total and marketable yields averaged 26.2 and 22.2 t/ha (Figure 2). Yields varied considerably from plot to plot but did not vary significantly ( $P>0.05$ ) with cropping history. There was a trend suggesting that the highest yields were in the perennial ryegrass and 'Hobson' fodder rape plots and lowest yields in the red clover and 'BQ Mulch' plots for total and marketable yield and the 75-280 size categories.

## Discussion

These studies examined the effects of different crop species that precede potatoes on disease and yield of potatoes. In the two trials at Bullarook, there were generally no major effects of the type of preceding crop on the incidence and severity of diseases of plants and tubers and on yields.

Relatively low disease levels were recorded at this site compared to those recorded in the disease survey (Section 4.1) suggest that disease pressure at this site is low. This may be because the site is cropped relatively infrequently with potatoes grown every 1 in 4 to 1 in 5 years. Levels of silver scurf, black scurf and powdery scab on tubers were consistent with levels recorded at other sites around the district. Although seed tubers are an important source of inoculum for silver scurf, black dot, Rhizoctonia canker and black scurf, the results of other field trials show that soil is the main source of disease in this cropping region (de Boer and Wicks 1994; de Boer 1997).

Studies of crop rotation generally report increasing levels of Rhizoctonia diseases with increasing cropping frequencies. The highest levels of disease occur in continuous potatoes or in 2-year rotations and less in 4, 5 and 6-year rotations (Frank and Murphy 1977; Scholte 1987; Scholte 1992; Gilligan *et al.* 1996). Gilligan *et al.* (1996) also reported different rates of loss of inoculum (as determined by a soil bioassay) during the intercrop periods in rotations, with a rapid fall to low levels after one year in a 6-year rotation (barley-potatoes) and after 2 years in a 4-year rotation. Generally, the frequency of potato cropping in a rotation cycle had a greater impact on the incidence and severity of Rhizoctonia damage than different rotation crops themselves (Scholte 1987; Scholte 1992).

The impact of an intercrop or rotation sequence on disease and yield in potatoes may depend on a number of factors which can have a direct or an indirect effect on both the pathogen and its environment. Different crop species may alter the physical, chemical and biological environment of the soil resulting in either a favourable or unfavourable environment for the pathogen. The environment may be conducive or suppressive, affecting the activity, survival, inoculum or virulence of the pathogen. *R. solani* is a soil saprophyte and may prefer to colonise some substrates over others.

Yields in Trial 2 (1998/99 season) were nearly half that of Trial 1 (1997/98 season). This is probably due to drier and warmer conditions in the 1998/99 season and the fact that the crop was grown under a limited capacity solid set irrigation system. Trial plots in Trial 1 were surrounded by a commercial crop and were watered under a commercial crop irrigation regime.

The reported effects of individual crop species in rotation on disease levels in potatoes vary. Leach *et al.* (1993) reported that, generally, there was no significant effect of rotation crops oats, lupin, buckwheat, broccoli peas and potato in a two year rotation (intercrop-potatoes) on soil populations of *R. solani* AG3. However, they reported that Rhizoctonia disease levels were lowest for broccoli-potatoes in chisel ploughed plots and highest for oats-potatoes in moldboard ploughed plots in the third year of the cycle. It was found that oats in a 1:2 year rotation with potatoes allows highly pathogenic strains of *R. solani* to become established (Specht and Leach 1987; Leach *et al.* 1993). However, Frank and Murphy (1977) suggest that over the long-term, oats may provide good pathogen and disease reduction. The attributes of broccoli that resulted in reduced disease are not known since the broccoli did not reduce soil

inoculum sufficiently to account for reduced disease and the virulence of the isolates from broccoli was no less than that from other crops (Leach *et al.* 1993). Natural fumigants released by brassicas may possibly have played a role here. Specht and Leach (1987) reported higher populations of soil *Rhizoctonia* spp. after buckwheat compared with other rotation crops (sweet corn, Japanese millet, spring oat, annual ryegrass, potato, in 2-year rotations with potato) but found that most isolates of the fungus were binucleate types. Buckwheat tissue is reported to provide one of the best substrates for *Rhizoctonia* colonisation while corn, oat or soybean tissues are poor substrates (Papavizas and Davey 1962; Papavizas 1970). Specht and Leach (1987) reported no significant effect of a one-year rotation with the different crops on the incidence of *Rhizoctonia* canker on stem and stolons. They also reported no significant effect on disease in potatoes of early incorporation of green crop residues versus the late incorporation of partially decomposed residues (after mowing) prior to cropping potatoes. In a Canadian study, potatoes grown after winter wheat had a higher incidence of *Rhizoctonia* disease than those grown after clover and ryegrass (Celetti *et al.* 1989a).

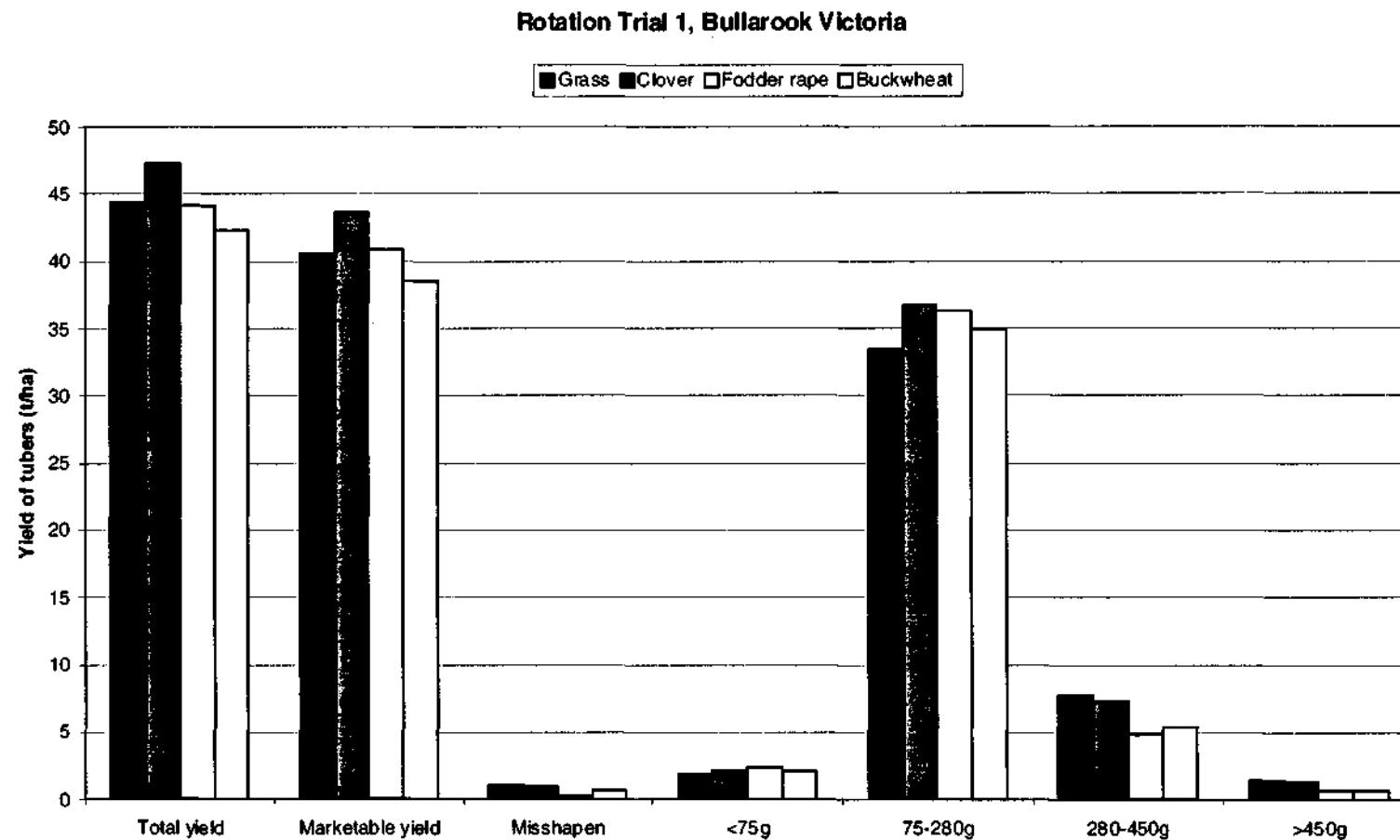
There were no apparent effects of biofumigant *Brassica* crops on disease and yield in this study. This issues if discussed in more detail in Section 4.3.3.

A study of *R. solani* in plots sown to potatoes and rotation crops showed that the fungus was able to grow and reproduce on the roots of *Brassica* species form an epiphytic relationship with its host (Section 4.4). This demonstrates that although *R. solani* AG3 is a potato pathogen it is able to develop a non-parasitic relationship with other crop species as described by Carling *et al.* (1986). This suggests that *Brassica* is a poor break crop for this pathogens. Further studies need to be done monitoring populations of the fungus through different rotation sequences.

**Table 16 Rotation Trial 1, Bullarook Victoria; Effects of crop rotation on the growth (stunting), disease on plants (Rhizoctonia stem canker, plants with aerial tubers) and on disease incidence and severity on progeny tubers (black scurf, black dot, silver scurf, powdery scab) of potatoes in 1997/98**

Rotation <sup>A</sup>	Stunting		Rhizoctonia damage		Mal-formed plants	Tuber diseases		Black dot		Silver scurf		Powdery scab	
	% plants affected	Severity (0-3)	% plants affected	Severity (0-4)		% tubers affected	Severity (0-4)						
					% plants affected								
Pasture-grass-potato	34.2	0.58	11.8	0.19	2.83	1.00	0.01	67.7	1.24	38.3	0.60	1.33	0.35
Pasture-clover-potato	24.0	0.38	6.55	0.20	2.00	1.33	0.03	70.8	1.24	37.2	0.58	0.67	0.01
Pasture-fodder-rape-potato	30.2	0.50	12.5	0.29	3.00	3.83	0.05	72.3	1.34	43.3	0.65	1.33	0.01
Pasture-buckwheat-potato	26.0	0.40	20.8	0.32	2.33	2.17	0.02	77.3	1.54	48.8	0.76	1.33	0.01
F test P value													
Istd. (P=0.05)	7.53	0.15	12.6	0.32	2.03	2.99	0.05	11.8	0.38	10.6	0.18	2.01	0.50

<sup>A</sup> Crops preceding potatoes. Cropping history: Pasture 1991-1996

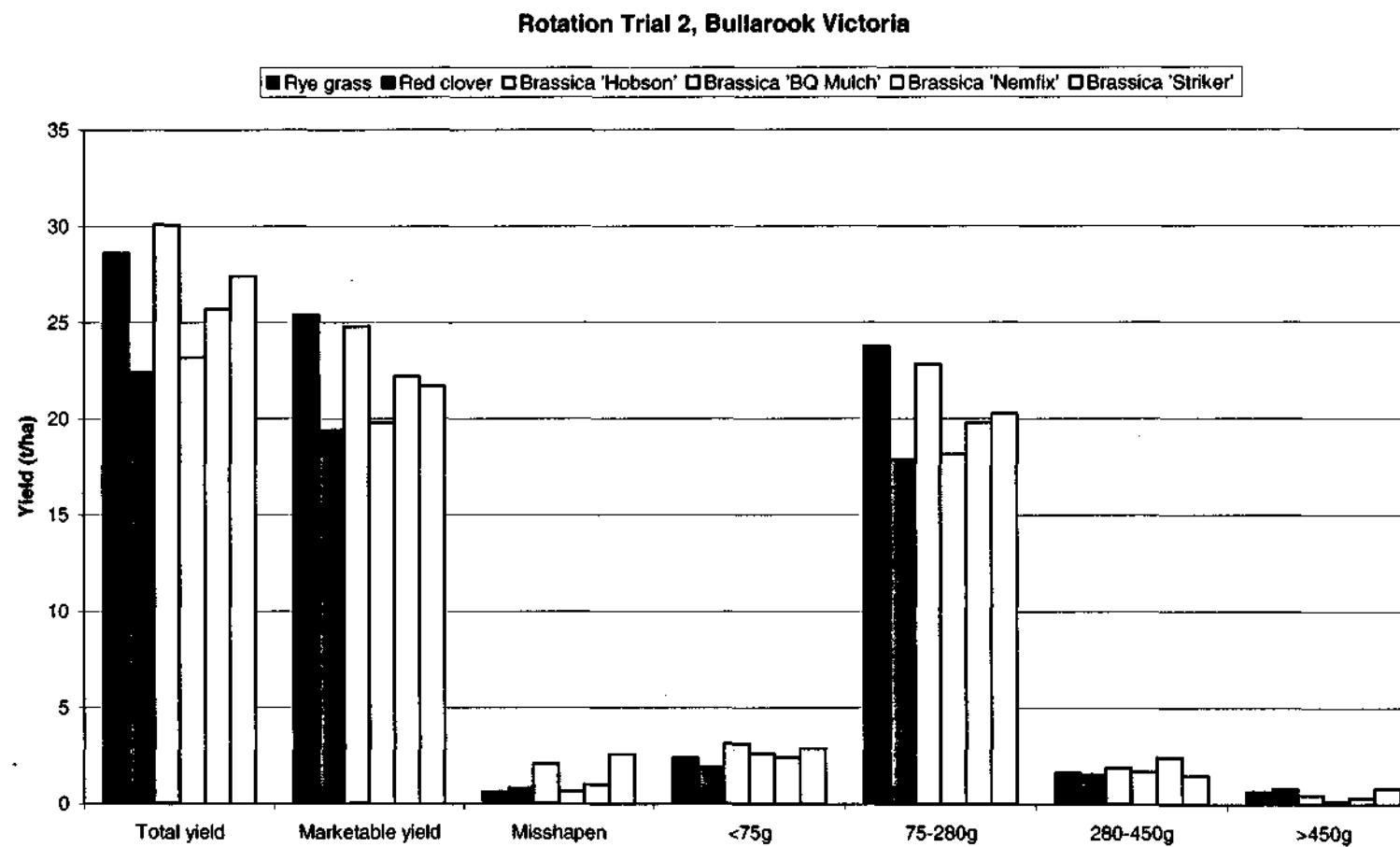


**Figure 1 Rotation Trial 1, Bullarook Victoria; Effects of different crops grown before potatoes on the total and marketable yields of potatoes and the yields in the different tuber size categories**

**Table 17 Rotation Trial 2, Bullarook Victoria; Effects of crop rotation on the growth (stunting), disease on plants (Rhizoctonia stem canker, plants with aerial tubers) and on the incidence and severity of diseases on progeny tubers (black scurf, black dot, silver scurf, powdery scab) of potatoes in 1998/99**

Rotation <sup>A</sup> Autumn97- Spring 97	Rhizoctonia damage				Mal- formed plants	Tuber diseases				Silver scurf				Powdery scab	
	Stunting		Stem canker			% plants affected	Severity (0-3)	% plants affected	Severity (0-4)	% tubers affected	Severity (0-4)	% tubers affected	Severity (0-4)	% tubers affected	Severity (0-4)
Grass-grass	15.0	0.18	29.2	0.73	9.0	17	0.21	70	1.0	32.0	0.39	5.0	0.05		
Clover- clover	19.0	0.30	47.9	1.04	15.5	27	0.37	72	1.0	23.0	0.28	4.0	0.04		
'Hobson'- 'Hobson' <sup>B</sup>	15.6	0.23	52.1	1.13	6.8	16	0.19	66	0.9	34.7	0.45	9.0	0.09		
Grass-'BQ Mulch' <sup>B</sup>	13.5	0.21	41.7	0.86	9.9	9	0.12	58	0.9	33.7	0.44	3.0	0.03		
Grass- 'Nemfix' <sup>C</sup>	18.6	0.24	41.7	1.09	9.7	13	0.17	60	0.8	23.3	0.29	3.0	0.03		
Wheat- 'Striker' <sup>B</sup>	19.5	0.27	43.7	1.06	15.0	20	0.25	74	1.0	31.7	0.41	9.0	0.09		
F-test	0.645	0.509	0.552	0.892	0.265	0.392	0.396	0.103	0.237	0.067		0.469	0.469		
I.s.d. (P=0.05)	8.85	0.134	25.09	0.794	8.71	17.26	0.240	13.26	0.217	9.80		8.36	0.084		

<sup>A</sup> Autumn and spring crops preceding potatoes. Cropping history: Pasture 1991/96, potato 1996/97<sup>B</sup>Fodder *Bassica* cultivars<sup>C</sup>Indian mustard



**Figure 2 Rotation Trial 2, Bullarook Victoria; Effects of different crops grown prior to potatoes on total and marketable yields of potatoes and yields in different size categories**

#### 4.2.4 Rotation trials at Virginia and Langhorne Creek in South Australia

##### Introduction

Rotation trials were established in two different potato cropping areas of South Australia, one at Langhorne Creek on the Lower Murray and the other at Woodside in the Adelaide Hills. The aim was to compare the effects of different cropping sequences involving pasture, cereals, fodder *Brassica* (fodder rape), Indian mustard and white radish on pathogen populations in soil and on disease and yield of potatoes. Different varieties and species of *Brassica* and the white radish were included so that their 'biofumigation' potential could be evaluated and compared.

##### Materials and Methods

###### *Experimental site, treatments and design*

A trial was established on a one-hectare site in a five-year-old Lucerne (*Medicago sativa*) pasture at Langhorne Creek, South Australia. The site had never been planted to potatoes before. Soil type at the site is a sandy loam (pH 5.8) with Mediterranean type climate (hot, dry summers and winter dominant rainfall). Twelve different rotation treatments were established at this site. Rotation treatments and sequences are illustrated in Table 18 and Table 20.

A second trial was established at a site with a sandy clay loam (pH 7.4) at Woodside which had been in pasture for 10 years, then planted to cereal rye (green manure crop) in the autumn of 1996 and to potatoes in the spring of 1996. Trial plots with eight different rotation treatments were established in the autumn of 1997 (Table 19 and Table 20).

Rotation crops in the two trials included a number of *Brassica* species: namely fodder rapes (*B. napus*), Indian mustards (*B. juncea*), and white mustard (*Rapheanus sativus*), various mixtures of fodder rapes (*B. napus* and *B. campestris*); cereals (wheat, oats, barley, cereal rye) and a pasture mixture (perennial ryegrass, cocksfoot, phalaris, subterranean clover).

All crop species (*Brassica*, cereals and pasture) were treated as if they were green manure crops. That is, the green crop was ploughed-in at around the 10% flowering stage or, in the case of cereals, when kernels were at the milky stage (Feeks scale 11.1), 45-50 days before planting potatoes. The various *Brassica* species and varieties and the white radish were selected for their different biofumigation potentials.

Details of crop species and crop management are presented in Table 21. Trials plots were 5.4 m (7 potato rows) by 100 m long. Trial design was a randomised block design replicated 6 times.

###### *Soil sampling and pathogen assessments*

Soil was sampled from individual plots at a minimum of 25 equally spaced sites in a 'W' pattern. Samples were taken at six times over each green manure/potato crop cycle at: about 14 days before planting the green manure crop; 50 days after emergence; 7 days prior to incorporation of the green manure crop; 35-56 days after green manuring; about 50 days after potato planting; and just prior to harvesting potatoes.

A 2.5cm diameter corer used to remove at least a 100 g soil from each sample site and samples for each plot were bulked. In the potato plots, soil was sampled within the root zone. Bulk samples (1 kg) were stored at 4°C until analysed for numbers of propagules of *V. dahliae*, *C. coccodes*, and *Pratylenchus* spp.

Sub-samples of 200-500 g of soil from each plot were air dried at room temperature at 15-25°C for 3-4 weeks to eliminate short-lived propagules (conidia and mycelial fragments), homogenised and sieved through a nest of sieves (850, 500, 250 and 45 µ mesh). Five 0.01 mg sub-samples of the soil that passed through the 45 µ sieve were each dispersed onto agar plates with NP10 selective media (Sorensen *et al.* 1991) using an Anderson Sampler (Butterfield and De Vay 1977). Plates were incubated at 22-25°C for 2 weeks and then examined under a bifocal microscope for micro sclerotia typical of *V. dahliae* and *C. coccodes* and the number of colony forming units (cfus) per gram of unsieved soil calculated.

The numbers of *Pratylenchus* nematodes were determined in two to five, 200 g sieved (2 mm mesh) sub-samples of soil from each plot. Nematodes were extracted from each sub-sample of soil in individual modified Baermann trays (Hooper and Evans 1993) (3 days incubation in water at 21-24° C).

#### *Harvest yield and disease assessments*

At harvest, 5 random, 3 m long strips were hand dug from each of 2 rows in each plot. Tubers from each plot were then sorted into different size categories, and the number and weight for each category recorded. A random sub-sample of 100 tubers was washed and assessed for the severity of skin blemishing diseases using a rating scale of 0-4, where ratings of 0, 1, 2, 3 and 4 were assigned to tubers 0, <3%, 3-10%, 10-25% and >25% of surface area affected with a symptom, respectively. The incidence of tubers with *V. dahliae* in the stem end was determined from a sample of 100 tubers. Segments of tissue were removed from the vascular ring at the stem end of each tuber, plated onto selective media and incubated from 14 days at 25°C.

## Results

### *Langhorne Creek*

A assessment of the incidence of potato plants with stem canker 14 weeks after planting, in the potato crop of 1999/2000, found the highest incidence in potatoes after oats, and wheat in treatments B, D and H (23%, 23 % and 25% plants affected). Incidence was lower (10-19% plants affected) ( $P \leq 0.05$ ) in all other treatments (not shown in Tables of Results).

Disease incidence and severity on potato tubers are presented in Table 22. Black dot and silver scurf were the most common diseases on tubers each first, second and third potato crops in the rotation cycle (1997/98, 1998/99 and 1999/2000). Disease incidence in the third year averaged 87-96% tubers affected with black dot and 49-92% tubers affected with silver scurf. The incidence of black scurf was low, moderate and high in each successive potato crop in the cycle. A low incidence of powdery scab was recorded in 1997/98 and a low incidence of common scab in 1999/2000. Generally disease incidence and severity did not vary significantly ( $P > 0.05$ ) with rotation treatments with the exception of black dot and black scurf in the second year and common scab in the third year ( $P \leq 0.05$ ). Generally, differences in disease incidence and severity of tuber diseases between rotation treatments could not be

correlated with specific rotation sequences comparing *Brassica* and other crop species. The incidence of recovery of *V. dahliae* from the stem end of tubers was very low by varied significantly ( $P \leq 0.05$ ) with rotation treatments in second and third year of potatoes.

Total yields were relatively high in the first year of potatoes (average 69-77 t/ha) and somewhat less in the second and third potato crops (35-56 t/ha and 33-48t/ha, respectively) (Table 23). Yields varied significantly with rotation treatments in the second and third potato crops. However, differences in yield between treatments could not be correlated with specific rotation sequences and the crop types preceding potatoes.

Numbers of cfus of *V. dahliae* and *C. coccodes*, and veriforms of *Pratylenchus* nematodes in soil over time in the different rotation treatments are illustrated in Figure 3, Figure 4 and Figure 5. The majority of nematodes found were identified as *P. crenatus*. A statistical comparison of pathogen populations at harvest time in the last potato crop in the rotation sequence is shown in Table 24. Counts of all three pathogens varied ( $P \leq 0.05$ ) with rotation. *V. dahliae* counts were lowest in the pasture, cereal and *Brassica* treatments (treatments C, D, K and L, respectively). This appeared to be the trend for these treatments over three years (Figure 3). The highest counts were recorded in two treatments involving cereals (treatments G and B), with counts in treatment G being consistently high over the three years. Counts of *C. coccodes* varied from 0.23 to 2.20 cfus/g soil and *P. crenatus* 0.62 to 3.00 veriforms/g of soil. Counts for both pathogens were consistently low over the three years in treatments under pasture (treatment C) which was not cropped to potatoes until the last season. Counts for both pathogens generally increased over the three years with increasing frequency of potato cropping. *P. crenatus* populations appear to peak at each post-green manure stage and post potato stage over the cropping cycles (Figure 5). Overall, there was no pattern indicating a correlation linking *Brassica* or cereal rotations, for instance, with soil populations of the three pathogens.

#### *Woodside, Adelaide Hills*

An assessment of the incidence of potato plants with stem canker 14 weeks after planting in the potato crop of 1998/99, found the highest incidence in potatoes after pasture and oats (treatments B and C) (25% and 30% plants affected). Incidence was lower (9-15% plants affected) ( $P \leq 0.05$ ) in all other treatments (not shown in Tables of Results).

Black dot, silver scurf and powdery scab were the most common diseases recorded on tubers at harvest in the 1997/98 season (Table 25). The incidence and severity of powdery scab, *V. dahliae* and pink rot varied significantly ( $P \leq 0.05$ ) with rotation treatments. The incidence of tubers with pink rot was nearly 10 times higher ( $P \leq 0.05$ ) in potatoes after cereal rye than in potatoes after *Brassica*. Nearly twice as many tubers had powdery scab in potatoes after fodder *Brassica* than after Indian mustard and cereal rye ( $P \leq 0.05$ ). Potatoes after cereal rye have nearly 50% more tubers with *V. dahliae* than potatoes after *Brassica*. The incidence and severity of black dot, silver scurf and black scurf did not vary significantly with rotation treatments.

In the 1998/99 season the incidence of diseases on tubers was relatively low overall, apart from the incidence of silver scurf (Table 25). However, approximately 50% more tubers were affected with black dot, common scab, black scurf and *V. dahliae* in potatoes after oats or pasture than in potatoes after *Brassica* (Table 25).

Total yields in the 1997/98 season were 30% higher in potatoes after *Brassica* than after cereal rye (Table 26). Total and marketable yields in the 1998/99 potato crop varied ( $P \leq 0.05$ ) with rotation treatment. However, there was no clear relationship between yield and rotation sequence.

Numbers of colony forming units of *V. dahliae* and *C. coccodes*, and veriforms of *Pratylenchus* nematodes in soil over time are illustrated in Figure 6, Figure 7 and Figure 8. As at Langhorne Creek, the majority of nematodes in the soil samples were identified as *P. crenatus*. Pathogen counts at harvest time in the last potato crop of the rotation sequence is shown in Table 27. The numbers of propagules of *V. dahliae* varied with rotation treatment ( $P \leq 0.05$ ) (1.0 to 4.4 cfus/g soil). This pattern was similar over the duration of the trial (Figure 6). Similarly, the populations of *C. coccodes* also varied with rotation ( $P \leq 0.05$ ) (6.2-21.0 cfus/g soil). The highest counts were in treatment E, in potatoes after oats and the lowest in potatoes after pasture. The counts were consistently low in the two pasture rotations (treatments A and B) over time but varied with time in other treatments (Figure 7). With both *V. dahliae* and *C. coccodes*, there were no consistent relationships linking crop types (e.g. *Brassica*, cereals, pasture) with differences in numbers of propagules in soil. The numbers of veriforms of *P. crenatus* were relatively low in all treatments and did not change greatly with time, except in the last cycle of green manure-potato when numbers increased, particularly in the pasture-potato treatment (treatment B) (Figure 8). These differences are reflected in the counts at harvest in the last season (Table 27). The counts were highest in potatoes after pasture (treatment B), 50% less ( $P \leq 0.05$ ) under pasture and potato after oats (treatments A and E, respectively) and lowest in the remaining treatments. There was no trend indicating that a relationship between the soil populations and the different groups of rotation crops.

## Discussion

Pathogen populations in soil, the incidence and severity of diseases in crops and on tubers and potato yields varied with rotation treatments in some seasons. However, there were no consistent correlations between these effects between different crop species of like groups such as cereals, pasture and *Brassica*. There was also no clear evidence that different *Brassica* crops grown before potatoes or over three cycles of *Brassica*-potato had a significant impact on disease and yield in comparison with other rotations such as those with pasture or cereal crops, for instance. Issues relating to the failure of *Brassica* to control diseases are discussed further in Section 4.3.3.

The incidence of black dot and silver scurf at Langhorne Creek were relatively high and not affected by the number of potato crops in the rotation over time (i.e. disease incidence did not increase with each successive potato crop as might have been expected in this case). These diseases are seed and soil-borne. The contribution of seed-borne inoculum to disease may have masked any effects of time and rotation treatments on soil-borne inoculum.

The pathogens *V. dahliae* and *P. crenatus* have a wide host range. This makes them difficult candidates for control with rotations. However, the key will be to determine which species make good host and allow the pathogens to grow and multiply and which make poor hosts.

**Table 18 Rotation treatments in a field trial at Langhorne Creek, Lower Murray, South Australia, 1996-2000 – Rotation Trial 1**

<b>Year</b>	<b>Treatment</b>											
	<b>C</b>	<b>D</b>	<b>A</b>	<b>B</b>	<b>E</b>	<b>F</b>	<b>L</b>	<b>K</b>	<b>G</b>	<b>H</b>	<b>J</b>	<b>I</b>
1996 (May-Oct)	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne
1996/97 (Nov-March)	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne	Lucerne
1997 (May-Oct)	Pasture	Pasture	Cereal Rye	Cereal Rye	Brassica Striker	Brassica Striker	Brassica Nemfix	Brassica Nemfix	Wheat	Wheat	Barley	Barley
1997/98 (Nov-March)	Pasture	Pasture	Potato	Potato	Potato	Potato	Potato	Potato	Fallow	Fallow	Fallow	Fallow
1998 (May-Oct)	Pasture	Pasture	Oats	Brassica BQ Fodder	Brassica BQ Fodder	Brassica BQ Mulch	Brassica Nemfix	Radish Weedcheck	Wheat	Brassica Nemfix	Barley	Oats
1998/99 (Nov-March)	Pasture	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato
1999 (May-Oct)	Pasture (sprayed early)	Oats	Oats	Oats	Brassica BQ Fodder	Brassica BQ Mulch	Brassica Nemfix	Radish Weedcheck	Barley	Wheat	Wheat	Brassica BQ Mulch
1999/00 (Nov-March)	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato	Potato

**Table 19 Rotation treatments in a field trial at Woodside, Adelaide Hills, South Australia, 1997/98-1998/99**

Year	Treatments							
	A	B	C	D	E	F	G	H
1996 (May-Oct)	Cereal Rye	Cereal Rye	Cereal Rye	Cereal Rye Potato	Cereal Rye Potato	Cereal Rye Potato	Cereal Rye Potato	Cereal Rye Potato
1996/97 (Nov-Mar)	Potato	Potato	Potato					
1997 (May-Oct)	Pasture	Pasture	Cereal Rye	Cereal Rye	Brassica Striker	Brassica Striker	Brassica Nemfix	Brassica Nemfix
1997/98 (Nov-Mar)	Pasture	Pasture	Potato	Potato	Potato	Potato	Potato	Potato
1998 (May-Oct)	Pasture	Pasture	Oats	Brassica BQ Fodder	Oats	Brassica BQ Mulch	Brassica Nemfix	Radish Weedcheck
1998/99 (Nov-Mar)	Pasture	Potato	Potato	Potato	Potato	Potato	Potato	Potato

**Table 20 Summary of rotation sequences in trials at Langhorne Creek and Woodside, South Australia**

(Ba = barley, Br = Brassica, Cr = cereal rye, F = fallow, O = oats, Pa = pasture, Po = potato, Ra = radish, W = wheat)

Langhorne Creek		Woodside, Adelaide Hills	
Treatment	Rotation sequence	Treatment	Rotation Sequence
A	Cr-Po-O-Po-O-Po	A	Cr-Po-Pa-Pa-Pa-Pa
B	Cr-Po-Br <sup>F</sup> -Po-O-Po	B	Cr-Po-Pa-Pa-Pa-Po
C	Pa-Pa-Pa-Pa-Pa-Po	C	Cr-Po-Cr-Po-O-Po
D	Pa-Pa-Pa-Po-O-Po	D	Cr-Po-Cr-Po-Br <sup>F</sup> -Po
E	Br <sup>F</sup> -Po-Br <sup>F</sup> -Po-Br <sup>F</sup> -Po	E	Cr-Po-Br <sup>F</sup> -Po-O-Po
F	Br <sup>F</sup> -Po-Br <sup>M</sup> -Po-Br <sup>M</sup> -Po	F	Cr-Po-Br <sup>F</sup> -Po-Br <sup>M</sup> -Po
G	W-F-W-Po-Ba-Po	G	Cr-Po-Br <sup>M</sup> -Po-Br <sup>M</sup> -Po
H	W-F-Br <sup>IM</sup> -Po-W-Po	H	Cr-Po-Br <sup>IM</sup> -Po-Ra <sup>R</sup> -Po
I	Ba-F-O-Po-Br <sup>F</sup> -Po		
J	Ba-F-Ba-Po-W-Po		
K	Br <sup>IM</sup> -Po-Ra <sup>R</sup> -Po-Ra <sup>R</sup> -Po		
L	Br <sup>IM</sup> -Po-Br <sup>IM</sup> -Po-Br <sup>IM</sup> -Po		

<sup>F</sup> Fodder *Brassica* spp.

<sup>M</sup> Fodder *Brassica* spp mixtures ('BQ Mulch™') specifically designed for use as a 'biofumigant green manure crop.'

<sup>IM</sup> Indian mustard ('Nemfix™')

<sup>R</sup> White radish ('Weedcheck™')

**Table 21 Details of experimental procedures for a rotation trial at Langhorne Creek, South Australia, 1996-2000**

Treatments	Rates of application
<b>Fertiliser</b>	
Hi-Fert 9:12:17:8 (Nov/potato planting)	600 kg/ha or 54 kgN: 72 kgP: 170 Kg/K
Urea 46% (Top-dress Brassicas in June)	600 kg/ha or 54 kgN: 72 kgP: 170 Kg/K
Urea 46% (Incorporation of cover crops Sept)	50 kg/ha or 23 kg N
<b>Sowing rates</b>	
'Striker' ( <i>Brassica napus</i> )	10 kg/ha
'Nemfix'™ ( <i>Brassica juncea</i> )	10 kg/ha
Cereal Rye ( <i>Secale cereale</i> )	62.5 kg/ha
'BQ Mulch'™ ( <i>Brassica napus</i> )	10 kg/ha
'BQ Fodder'™ ( <i>Brassica napus</i> )	10 kg/ha
'Weedcheck'™ ( <i>Raphanus sativus</i> )	20 kg/ha
'Coolabah' oats ( <i>Avenaceum sativum</i> )	80 kg/ha
Wheat ( <i>Triticum aestivum</i> )	100 kg/ha
Barley ( <i>Hordeum vulgare</i> )	80 kg/ha
'Hills Drygrown No.2 & No.4'™ pasture mix (Perennial ryegrass, cocksfoot, phalaris, subterranean clover)	20 kg/ha
'Coliban' Potatoes	3200 kg/ha (set 275mm, row 800mm)
<b>Chemical Rates</b>	
Score® (250g/L a.i. Difenoconazole) (Target spot)	0.5 L/ha 250-300 Kpa
Bravo® (500g/L a.i chlorthalonil) (Target spot)	2.6 L/ha
Roundup Glyphosphate 360®	3 L/ha (25 – 100L water/ha)
Sencor 480 SC® (metrabuzin)	1.1 L/ha (50 – 100L water/ha)
Reglone diquat	3.5 L/ha
<b>Irrigation Rates</b>	
As applied by the grower	

**Table 22 The effects of rotation treatments on the incidence and severity of disease on progeny potato tubers at harvest time in a field trial at Langhorne Creek, South Australia, 1996-2000**

Year	Treatment <sup>b</sup>	Black Dot		Silver Scurf		Common Scab		Black Scurf		Verticillium	Powdery Scab
		% tubers affected	Severity (0-4) <sup>a</sup>								
1999/ E	Brassica <sup>c</sup>	3	91	1.6	74	0.7	10.7a	0.1	39	0.9	3.0b
2000 F	Brassica <sup>c</sup>	3	95	1.6	76	0.7	2.3b	0.1	27	0.7	1.2b
K	Brassica <sup>c</sup>	3	92	1.8	73	0.7	1.5b	0.1	27	0.6	3.4b
L	Brassica <sup>c</sup>	3	96	1.9	70	0.7	1.4b	0.1	50	1.1	1.0c
I	Brassica	2	94	1.7	72	0.7	3.4b	0.1	36	0.8	2.2b
A	Oats	3	92	1.4	49	0.5	3.1b	0.1	41	0.9	10.4a
B	Oats	3	96	1.5	57	0.6	1.6b	0.1	43	0.9	2.4b
D	Oats	2	87	1.7	92	0.9	6.8a	0.1	41	0.8	2.4b
G	Barley	2	91	1.6	64	0.6	2.7b	0.1	48	0.9	3.2b
H	Wheat	2	91	1.5	63	0.6	2.7b	0.1	43	0.8	11.3a
J	Wheat	2	97	1.7	71	0.7	2.9b	0.1	35	0.7	1.3b
C	Pasture	1	89	1.6	92	0.9	3.1b	0.1	41	0.8	2.5b
LSD (P=0.05)			n.s.	n.s.	n.s.	5.101	n.s.	n.s.	n.s.	2.121	-
1998/ B	Brassica	2	89a	1.2d	58	0.5	0	0	25b	0.4ab	1.8c
1999 E	Brassica <sup>c</sup>	2	75ab	0.8d	76	0.8	0	0	22b	0.3b	2.3c
F	Brassica <sup>c</sup>	2	84a	1.7cd	81	0.6	0	0	22b	0.3b	3.5bc
K	Brassica <sup>c</sup>	2	79ab	1.7cd	84	0.6	0	0	24ab	0.3b	3.2bc
L	Brassica <sup>c</sup>	2	81ab	3.2ab	79	0.5	0	0	17bc	0.3b	4.3b
H	Brassica	1	84a	3.7a	73	0.6	0	0	11bc	0.1bc	4.0b
A	Oats	2	81ab	2.8ab	54	0.6	0	0	36a	0.4ab	7.5a
I	Oats	1	83a	2.5bc	68	0.5	0	0	36a	0.5a	6.3a
J	Barley	1	68b	1.0d	78	0.6	0	0	5c	0.1c	1.3c
G	Wheat	1	64b	0.7d	77	0.7	0	0	24ab	0.3ab	0.6c
D	Pasture	1	75ab	1.0d	86	0.6	0	0	18bc	0.2b	1.2c
LSD (P=0.05)		14.76	1.013	n.s.	n.s.	n.s.	n.s.	13.31	0.17	1.745	-
1997/ A	Rye		74.8a	4.33a	63.5	0.9	0	0	14	0.4a	1.4
1998 E	Brassica		64.2ab	1.33b	54.4	0.7	0	0	11	0.2ab	0.8
L	Brassica		56.2b	1.33b	53.6	0.8	0	0	5	0.1b	0.6
LSD (P=0.05)		13.37	2.112	n.s.	n.s.	n.s.	n.s.	n.s.	0.1986	n.s.	n.s.

<sup>a</sup> Severity rating scale 0 to 4: 0, no diseases; 1, <2%; 2, 3-10%; 3, 11-25%, 4 >25% of tuber surface affected. <sup>b</sup> Rotation treatment and the crop preceding potatoes. Numbers after crop represent the number of potato crops in the rotation cycle. <sup>c</sup> Brassica-potato rotations. Values followed by the same letter are not significantly different from each other at P=0.05

**Table 23 The effects of rotation treatments on total and marketable yield potatoes in a field trial at Langhorne Creek, South Australia, 1996-2000**

Ba, barley; Br, Brassica Cr, cereal rye; F, fallow; O, oats; Pa, pasture; Po, potato; Ra, radish; W, wheat; <sup>F</sup> Fodder *Brassica* spp; <sup>M</sup> Fodder *Brassica* spp mixtures ('BQ Mulch<sup>TM</sup>) specifically designed for use as a 'biofumigant green manure crop'; <sup>IM</sup> Indian mustard ('Nemfix<sup>TM</sup>); <sup>R</sup> White radish ('Weedcheck<sup>TM</sup>)

Treatment	Rotation sequence	Potatoes 1997/98		Potatoes 1998/99		Potatoes 1999/2000	
		Total yield (t/ha)	Marketable yield (t/ha)	Total yield (t/ha)	Marketable yield (t/ha)	Total yield (t/ha)	Marketable yield (t/ha)
A	Cr-Po-O-Po-O-Po	68.7	59.7	49b	40b	35b	26b
B	Cr-Po-Br <sup>F</sup> -Po-O-Po	-	-	36c	29c	33b	23b
C	Pa-Pa-Pa-Pa-Pa-Po	-	-	-	-	34b	26b
D	Pa-Pa-Pa-Po-O-Po	-	-	38c	30c	51a	39ab
E	Br <sup>F</sup> -Po-Br <sup>F</sup> -Po-Br <sup>F</sup> -Po	66.9	58.6	43bc	37b	41ab	32ab
F	Br <sup>F</sup> -Po-Br <sup>M</sup> -Po-Br <sup>M</sup> -Po	-	-	36c	30c	43ab	35ab
G	W-F-W-Po-Ba-Po	-	-	54ab	45ab	47ab	37ab
H	W-F-Br <sup>IM</sup> -Po-W-Po	-	-	56a	47a	38b	30b
I	Ba-F-O-Po-Br <sup>F</sup> -Po	-	-	46b	37bc	51a	42a
J	Ba-F-Ba-Po-W-Po	-	-	49ab	40b	48ab	40ab
K	Br <sup>IM</sup> -Po-Ra <sup>R</sup> -Po-Ra <sup>R</sup> -Po	-	-	35	26c	33b	25b
L	Br <sup>IM</sup> -Po-Br <sup>IM</sup> -Po-Br <sup>IM</sup> -Po	77.0	67.9	49ab	41ab	39b	31b
LSD (P=0.05)		n.s.	n.s.	7.148	6.643	11.66	10.52

Values followed by the same letter are not significantly different from each other at P=0.05

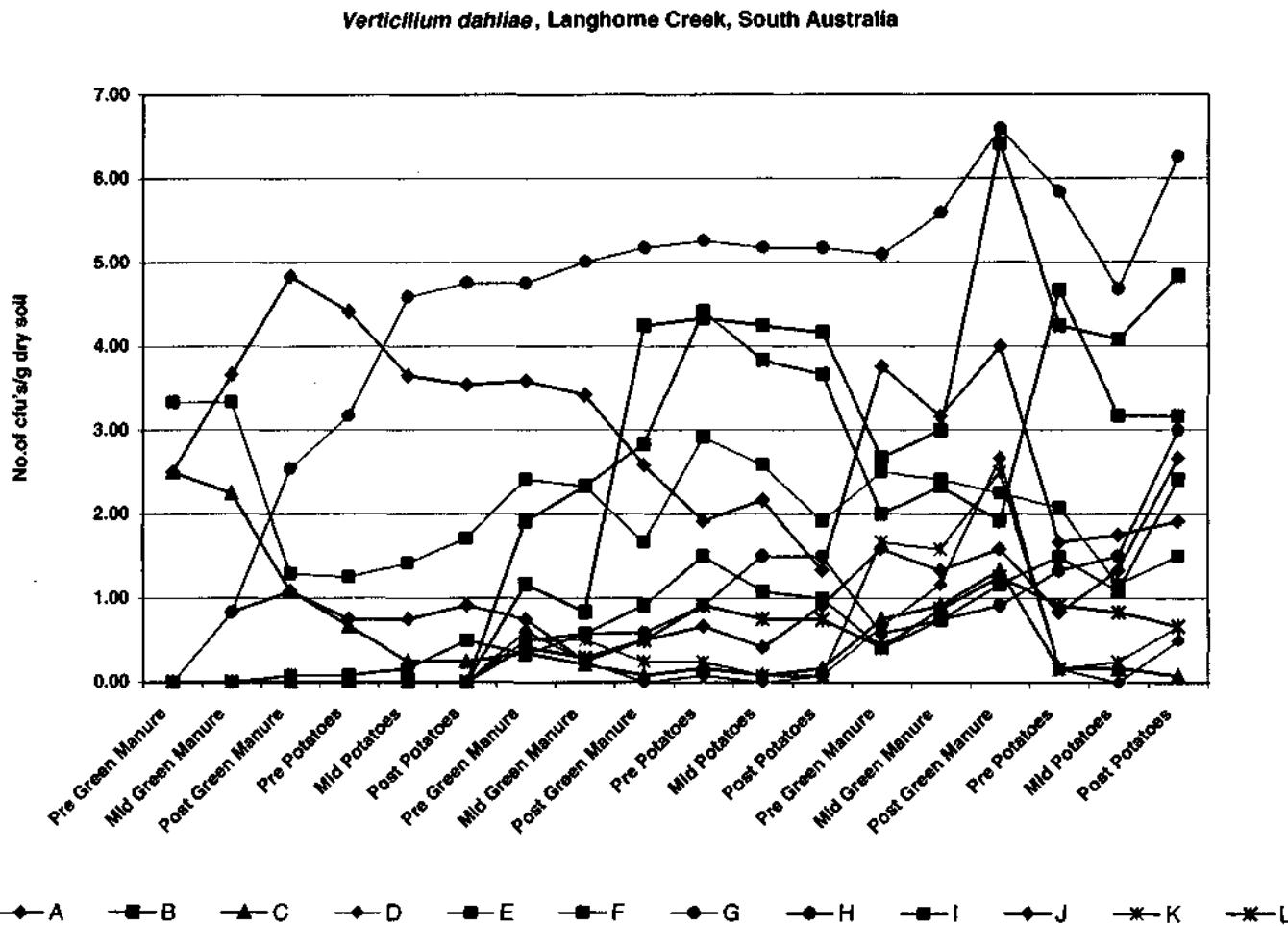
**Table 24 The effects of rotation treatments on the number of propagules of *Verticillium dahliae*, *Colletotrichum coccodes* and *Pratylenchus crenatus* at the harvest of potatoes, Langhorne Creek, 1999/2000**

<b>Treatment<sup>A</sup></b>		<i>Verticillium dahliae</i> (No. cfus/g dry soil)	<i>Colletotrichum coccodes</i> (No. cfus/g dry soil)	<i>Pratylenchus crenatus</i> (No. veriforms/g dry soil)
E	Brassica <sup>B</sup>	3	1.50de	0.93d
F	Brassica <sup>B</sup>	3	3.17c	1.22cd
K	Brassica <sup>B</sup>	3	0.67e	0.85d
L	Brassica <sup>B</sup>	3	0.67e	0.37c
I	Brassica	2	2.42cd	1.37c
A	Oats	3	2.67cd	2.15a
B	Oats	3	4.83b	1.77b
D	Oats	2	0.50e	1.18cd
G	Barley	2	6.25a	2.20a
H	Wheat	2	3.00c	2.00ab
J	Wheat	2	1.92d	1.35c
C	Pasture	1	0.08e	0.23e
<b>LSD (P&lt;0.05)</b>		1.061	0.352	0.323

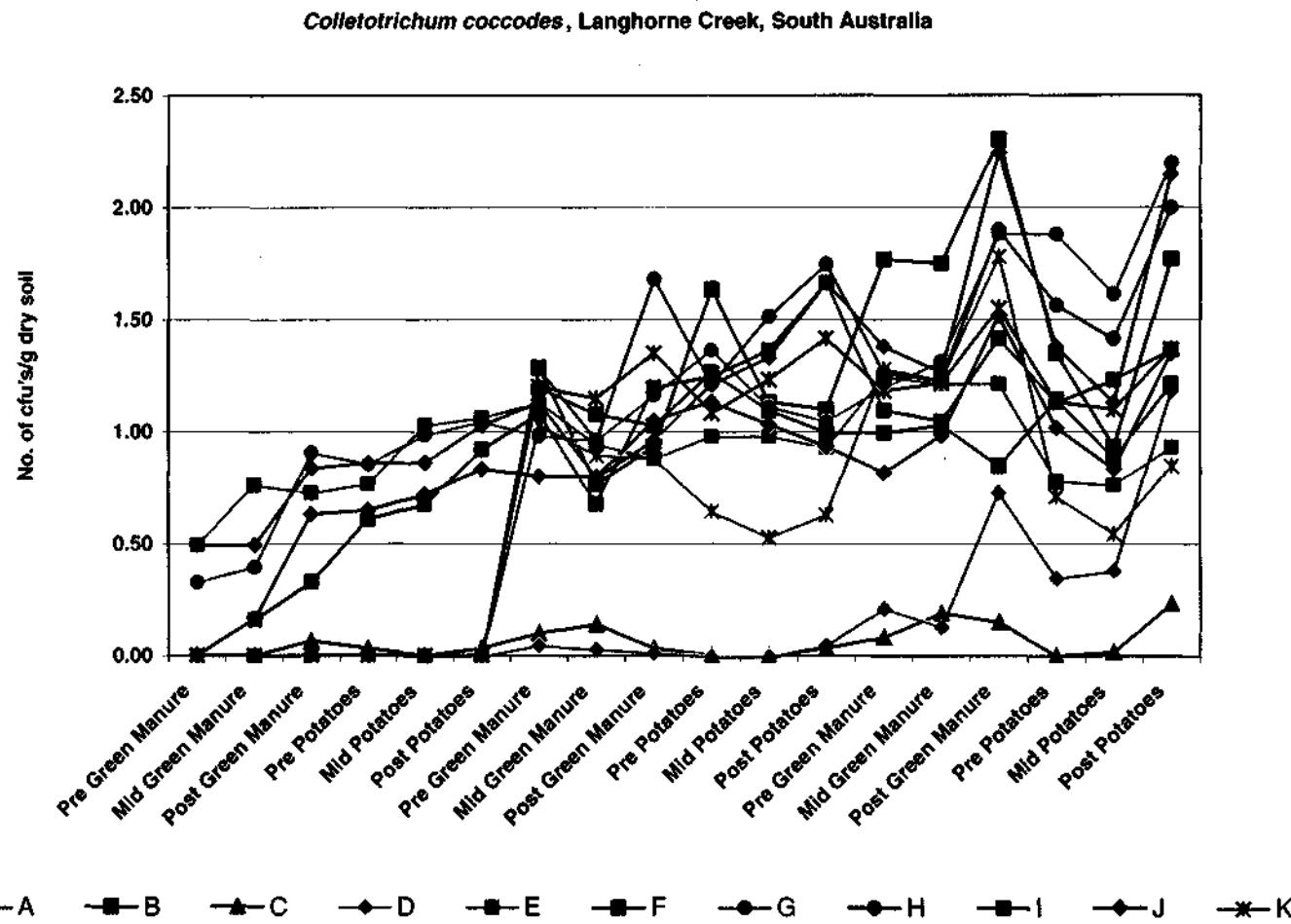
<sup>A</sup> Rotation treatment and the crop preceding potatoes. Number represents the number of potato crops in the rotation cycle

<sup>B</sup> Brassica-potato rotations.

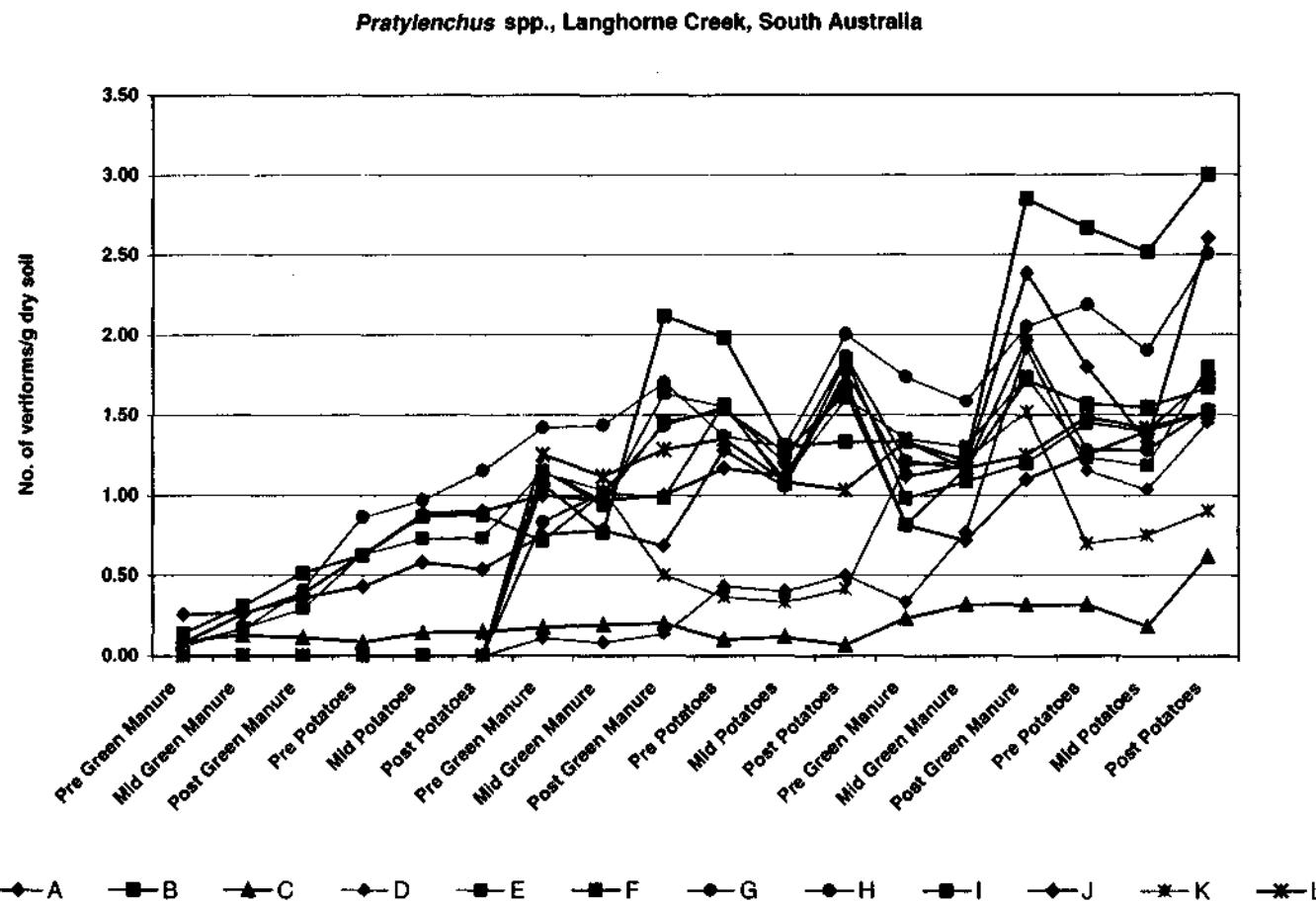
Values followed by the same letter are not significantly different from each other at P=0.05



**Figure 3** The numbers of propagules of *Verticillium dahliae* in soil under different rotation sequences (represented by letters in the legend) over three seasons (Autumn 1997-Spring/Summer 1999) in a field trial at Langhorne Creek, South Australia



**Figure 4** The numbers of propagules of *Colletotrichum coccodes* in soil under different rotation sequences (represented by letters in the legend) over three seasons (Autumn 1997-Spring/Summer 1999) in a field trial at Langhorne Creek, South Australia



**Figure 5** The numbers of *Pratylenchus* spp. nematodes in soil under different rotation sequences (represented by letters in the legend) over three seasons (Autumn 1997-Spring/Summer 1999) in a field trial at Langhorne Creek, South Australia

**Table 25 The effects of rotation treatments on disease of progeny tubers at harvest in a field trial at Woodside, Adelaide Hills, South Australia, 1997/98-1998/99**

Treatment <sup>B</sup>	Black Dot		Silver Scurf		Common Scab		Black Scurf		Powdery Scab	Verticillium	Pink Rot
	% tubers affected	Severity <sup>A</sup>	% tubers affected	% tubers affected	% tubers affected						
<b>1997/98</b>											
E Brassica	2	60	1.0	37	0.6	0	0	2.8	0.1	30.5a	4.2b
F Brassica	2	60	1.0	37	0.6	0	0	2.8	0.1	30.5a	4.2b
G Brassica	2	53	0.9	30	0.5	0	0	10.2	0.2	14.3b	6.5b
H Brassica	2	53	0.9	30	0.5	0	0	10.2	0.2	14.3b	6.5b
C Rye	2	66	1.0	40	0.7	0	0	4.7	0.1	12.8b	16.5a
D Rye	2	66	1.0	40	0.7	0	0	4.7	0.1	12.8b	16.5a
LSD (P=0.05)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	15.27	3.837	12.28
<b>1998/99</b>											
D Brassica	3	6.0b	0.07ab	32	0.14	7bc	0.7ab	2c	-	0	5.7b
F Brassica	3	4.3b	0.04b	31	0.06	5c	0.6b	1c	-	0	6.5b
G Brassica	3	5.7b	0.03b	44	0.08	9b	0.9ab	0c	-	0	7.2b
H Brassica	3	5.5b	0.00 b	28	0.03	4c	0.4b	0c	-	0	5.2b
C Oats	3	11.3a	0.13a	40	0.10	12a	1.1a	6b	-	0	21.2a
E Oats	3	11.3a	0.13a	40	0.10	12a	1.1a	6b	-	0	21.2a
B Pasture	2	9.0a	0.00 b	20	0.01	10ab	1.0a	10a	-	0	17.8a
LSD (P=0.05)	2.948	0.0821	n.s.	n.s.	2.121	0.4460	3.241		n.s.	4.516	n.s.

<sup>A</sup> Severity rating scale 0 to 4: 0, no disease; 1, <2%; 2, 2-10%; 3, 11-25%, 4 >25% of tuber surface affected<sup>B</sup> Rotation treatment and the crop preceding potatoes. No. of potato crops in the rotation sequence.

n.s. Not statistically significant, F test P value &gt;0.05

Values followed by the same letter are not significantly different from each other at P=0.05

**Table 26 The effects of rotation treatments on the total and marketable yield of tubers in a field trial at Woodside, Adelaide Hills, South Australia, 1997/98-1998/99**

Ba, barley; Br, Brassica Cr, cereal rye; F, fallow; O, oats; Pa, pasture; Po, potato; Ra, radish; W, wheat; <sup>F</sup> Fodder *Brassica* spp; <sup>M</sup> Fodder *Brassica* spp mixtures ('BQ Mulch™') specifically designed for use as a 'biofumigant green manure crop'; <sup>IM</sup> Indian mustard ('Nemfix™'); <sup>R</sup> White radish ('Weedcheck™')

Treatment	Rotation sequence	Potatoes 1997/98		Potatoes 1998/99	
		Total yield (t/ha)	Marketable yield (t/ha)	Total yield (t/ha)	Marketable yield (t/ha)
B	Cr-Po-Pa-Pa-Po	-	-	15.3b	9.5b
C	Cr-Po-Cr-Po-O-Po	18.2b	-	18.0ab	14.1a
D	Cr-Po-Cr-Po-Br <sup>F</sup> -Po	18.2b	-	17.5ab	12.6ab
E	Cr-Po-Br <sup>F</sup> -Po-O-Po	24.4a	-	18.0ab	14.1a
F	Cr-Po-Br <sup>F</sup> -Po-Br <sup>M</sup> -Po	24.4a	-	17.1ab	11.7ab
G	Cr-Po-Br <sup>IM</sup> -Po-Br <sup>IM</sup> -Po	26.1a	-	11.6b	9.0b
H	Cr-Po-Br <sup>IM</sup> -Po-Ra <sup>R</sup> -Po	26.1a	-	19.1a	13.1a
LSD (P=0.05)		5.61	-	3.721	3.413

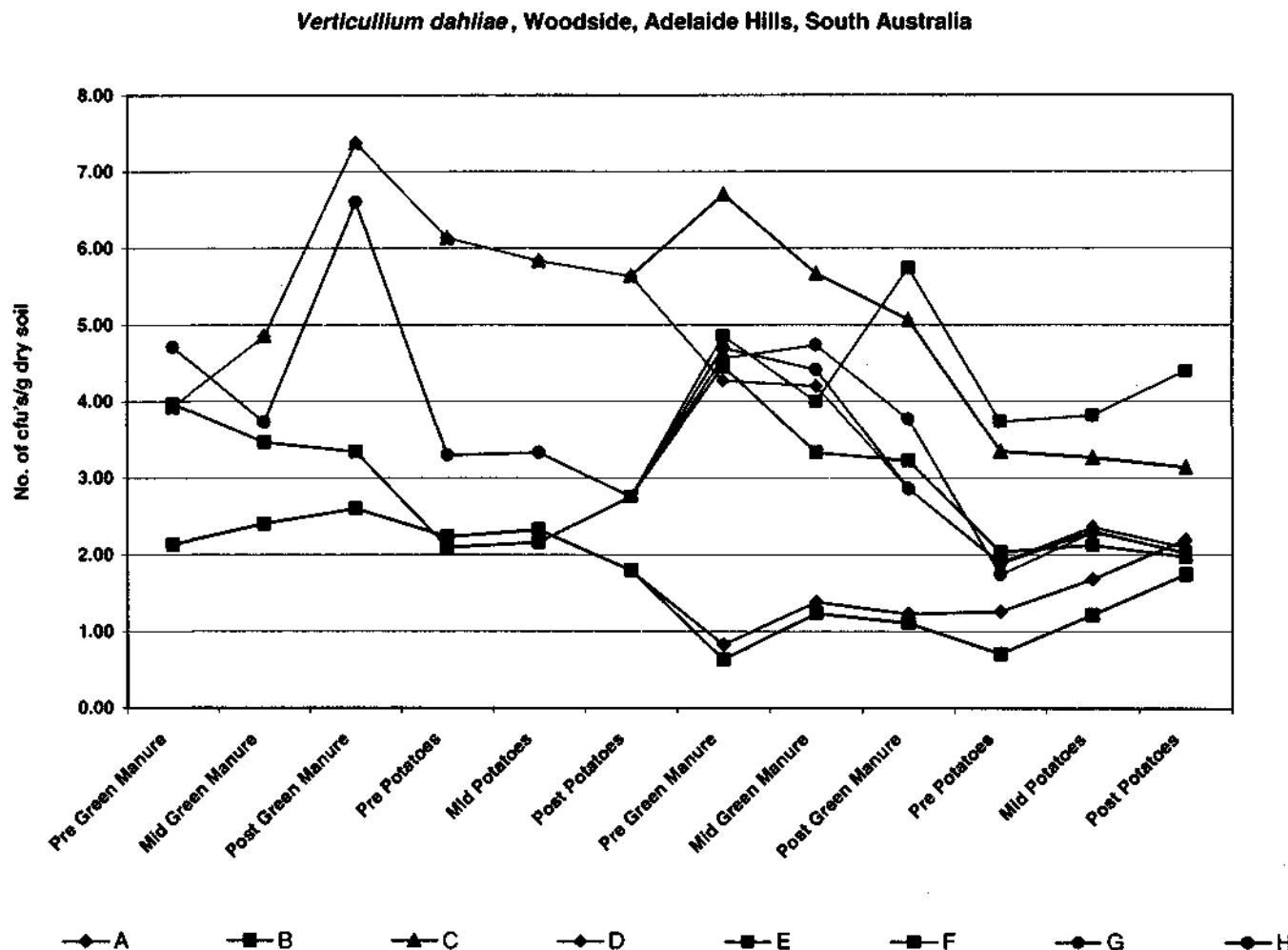
Values followed by the same letter are not significantly different from each other at P=0.05

**Table 27 The effects of rotation treatments on the number of propagules of *Verticillium dahliae*, *Colletotrichum coccodes* and *Pratylenchus crenatus* at the harvest of potatoes, Woodside, 1998/99**

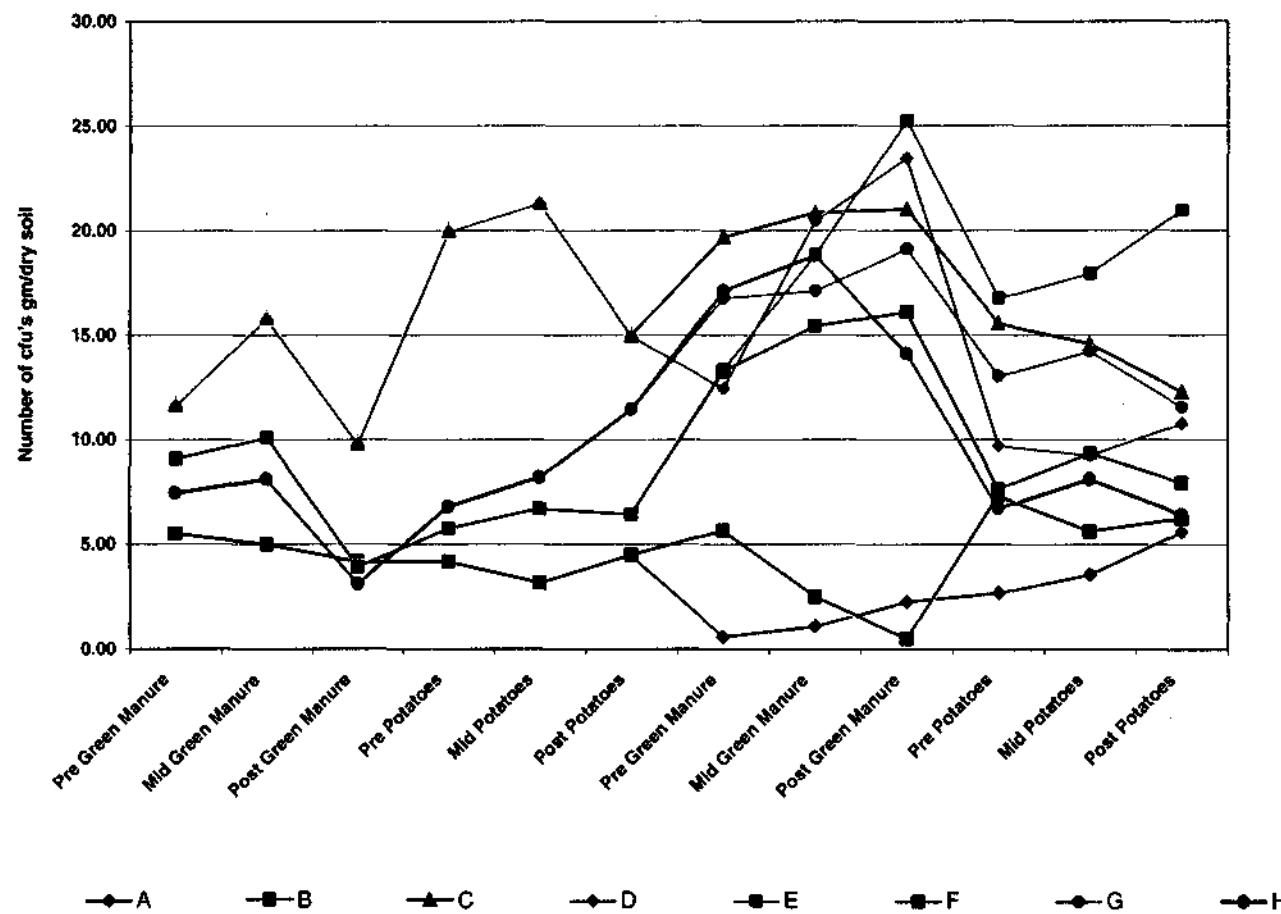
Treatment <sup>A</sup>		<i>Verticillium dahliae</i> (No. cfus/g dry soil)	<i>Colletotrichum coccodes</i> (No. cfus/g dry soil)	<i>Pratylenchus crenatus</i> (No veriforms/g dry soil)
D	Brassica	3	2.1c	10.8bc
F	Brassica	3	1.0c	8.0bc
G	Brassica	3	2.0c	11.6bc
H	Brassica	3	2.0c	6.5bc
C	Oats	3	3.1b	12.3b
E	Oats	3	4.4a	21.0a
A	Pasture	-	2.2c	5.7bc
B	Pasture	2	1.7c	6.2c
LSD (P<0.05)		0.761	3.612	0.779

<sup>A</sup> Rotation treatment and the crop preceding potatoes. Number represents the number of potato crops in the rotation cycle

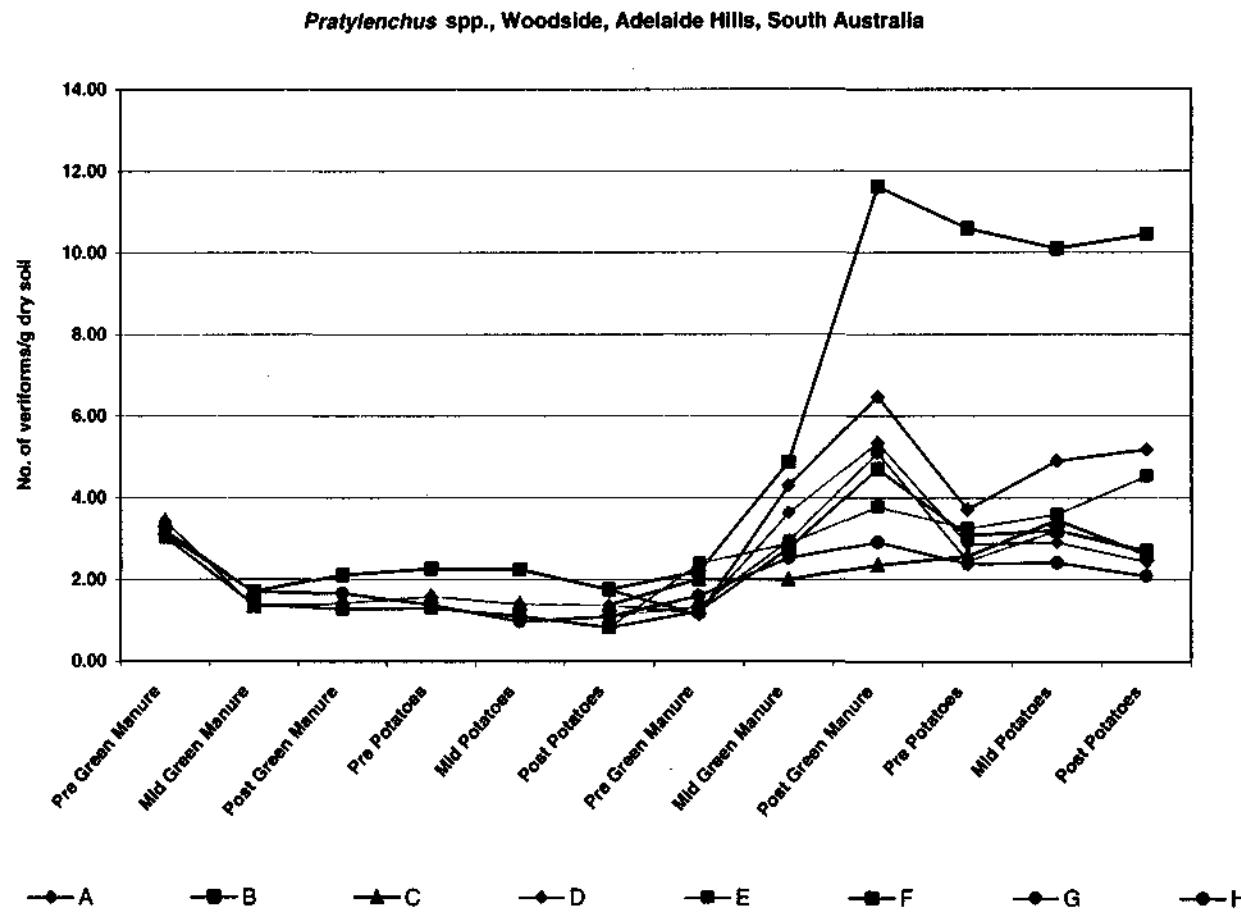
Values followed by the same letter are not significantly different from each other at P=0.05



**Figure 6** The number of propagules of *Verticillium dahliae* in soil under different rotation sequences (represented by letters in the legend) over two seasons (Autumn 1997-Spring/Summer 1998) a field trial at Woodside, Adelaide Hills, South Australia.



**Figure 7** The number of propagules of *Colletotrichum coccodes* in soil under different rotation sequences (represented by letters in the legend) over two seasons (Autumn 1997-Spring/Summer 1998) a field trial at Woodside, Adelaide Hills, South Australia



**Figure 8** The number of *Pratylenchus* spp. nematodes in soil under different rotation sequences (represented by letters in the legend) over two seasons (Autumn 1997-Spring/Summer 1998) in a field trial at Woodside, Adelaide Hills, South Australia

### **4.3 The effects of biofumigation on soil-borne diseases of potatoes**

#### **Summary**

Laboratory experiments demonstrated that volatile products released from Indian mustard seed meal and from the tissues of Indian mustard, fodder *Brassica* and white radish plants inhibited the growth of the fungal pathogens *Rhizoctonia solani*, *Colletotrichum coccodes*, *Verticillium dahliae*, *Phytophthora erythroseptica* and *Phytophthora cryptogea*. Indian mustard meal was significantly more inhibitory than freeze-dried plant issues. The different fungi varied in their sensitivity to different tissues depending on the source of the material (seed meal, leaf, stem and root). Tissues from *Brassica* plants sprayed with a herbicide were less inhibitory than tissues from unsprayed plants.

When incorporated into a potting media that was artificially inoculated with potato pathogens, mustard meal reduced the incidence of diseases on potato tubers at rates equivalent to 3 t/ha. This demonstrated the potential of mustard meal to control diseases in the field. However, the treatment was phytotoxic, reducing emergence and growth of potato plants. Mustard meal incorporated into soil just before sowing potatoes in field trials in Victoria and South Australia, generally did not affect disease incidence and severity in the potato crop. In one trial, mustard meal at 1200 kg/ha reduced emergence, plant growth and yield indicating that the meal produced biocidal compounds in soil.

Different varieties of *Brassica* (*B. juncea*, *B. napus*, *Raphanus sativus*) were used in rotation trials in Victoria and South Australia as green manure crops prior to planting potatoes. There was no clear evidence linking the use of biofumigant crops with reduced incidence and severity of diseases and improved yields. Further research should be more focused at measuring the concentrations of biocidal chemicals released in soil when *Brassica* crops are incorporated, their impact on pathogen populations and on other potential benefits of green manure crops in general.

#### **Background**

Ever since CSIRO scientists coined the term 'biofumigation', potato farmers have been taken by the concept of planting crops that could 'fumigate' soil. *Brassica* crops have been widely planted in potato production areas for disease control, despite the lack of evidence supporting the concept of biofumigation in commercial practice. Fodder *Brassica* crops (rape and turnip) are traditionally grown after potatoes to fatten livestock in some districts in Victoria. There is anecdotal evidence passed down from an older generation that growing *Brassica* is beneficial to potato production. Equally there is anecdotal evidence to the contrary. Most research on the potential of *Brassica* crops to control pathogens in Australia has been focused on field crop production (Angus *et al.* 1994). There are many reports in the literature demonstrating inhibition of bacterial, fungal and nematode pathogens by *Brassica* tissue in the laboratory and the glasshouse. Apart from the possible role of biofumigation in controlling take-all in cereals in Australia, there is very little evidence that *Brassica* crops control diseases in the field. Furthermore, there were very few reports of the effects of *Brassica* on potato pathogens and diseases at the start of this project.

Kirkegaard *et al.* (1996) demonstrated that volatile compounds released from freeze dried root and shoot tissues of canola (*B. napus*) and Indian mustard (*B. juncea*) and Indian mustard seed meal tissues inhibited the growth of several important cereal pathogens. Similar

tests conducted on potato pathogens are reported here. The effects of Indian mustard meal as a soil amendment were also evaluated. Several different types of *Brassica* crops with different varying biofumigation potential were planted as green manure crops prior to potatoes in rotation trials in Victoria and South Australia.

#### 4.3.1 The effects of volatile compounds from *Brassica* plants on the growth of potato pathogens in vitro

A series of laboratory experiments were conducted to test the effects of volatile hydrolysis products released from defatted mustard meal tissues or from freeze dried root, stem and shoots tissues of field-grown Indian mustard (*B. juncea*), fodder *Brassica* (*B. napus*) and white radish (*Raphanus sativus*) on the growth of fungal pathogens of potatoes. The methods were based on those of Kirkegaard *et al.* (1996).

*Brassica* tissue in amounts of 0, 10, 25, 50 or 100 mg was placed into 2 cm diameter plastic vessels in the centre of upturned Petri-dish lids. Sterile water was added to the mustard meal in each vessel at volumes of 50, 125, 250, and 500 µL, respectively, with 2000 µL of sterile water added to vessels with no meal. The bottom of Petri dish plates with potato dextrose agar, each with a 5mm plug of a 5 to 7 day-old culture of a potato pathogen, were placed upside-down over the upturned lids containing the *Brassica* tissues. The plates were sealed with plastic film to prevent the escape of volatile products and incubated in the dark at 22°C. The radial growth of each fungus was measured by taking two radial transects of the colonies at various times after adding water to hydrolyse the *Brassica* tissue. Growth inhibition was expressed as a percentage of the growth of controls without *Brassica* tissue. Data were analysed by ANOVA as replicated complete randomised blocks using Genstat for Windows 5<sup>th</sup> Edition™ (Lawes Agricultural Trust, Rothamsted Experimental Station).

##### *Experiment 1 – the effects of mustard seed meal on the growth of potato pathogens*

The effect of volatile products from defatted Indian mustard meal (0, 10, 25, 50 or 100 mg) was tested on cultures of the fungi *Verticillium dahliae*, *Colletotrichum coccodes* and *Rhizoctonia solani* AG3. The radial growth of each culture and the number of microsclerotia of *Verticillium dahliae* and *Colletotrichum coccodes* produced in culture were recorded 6, 12, 24, 48, 96, and 192 hrs after hydrating mustard meal.

The production of toxic volatile hydrolysis products from the hydrated mustard meal was evident by the reduced growth of the different fungi in culture. The radial growth of all pathogens was affected and, generally, the percentage inhibition increased with increasing rates of mustard meal (Figure 9). *R. solani* AG3 was most sensitive with the greatest growth reduction (89% of the control), when exposed to 100 mg of mustard meal for 192 hours. *C. coccodes* was least sensitive (40% reduction) and *V. dahliae* was moderately sensitive (60% reduction). The meal affected the production of microsclerotia in culture, with *C. coccodes* being more sensitive than *V. dahliae* (Figure 9).

In a related study as part of a student project, the effects of mustard meal on the growth of *C. coccodes* and *R. solani* were compared *in vitro* (Laura Seymour unpublished). The rates of meal and the experimental procedure were as described for Experiment 1. Growth of *R. solani* was completely inhibited at 25 mg of mustard meal compared with *C. coccodes* at 100 mg, indicating that the latter was less sensitive to the volatile products than *R. solani*.

**Experiment 2 – effects of volatile products from the leaf, stem and root tissues of Brassica species on the growth of soil-borne potato pathogens**

The effects of volatile products from the freeze dried leaf, stem and root tissues from *B. napus*, *B. juncea*, *R. sativus* and oats (*Avena sativa*) and from Indian mustard seed meal and a pelletised formulation of a mustard seed meal/neem mixture (25% meal: 75% neem; *Azadirachta indica*) were compared. Oats was used as a control since this species does not produce glucosinolates.

Leaf, stem and root tissue was collected from green manure crops in rotation trial plots (Section 4.2.4). *Brassica* (*B. juncea* and *B. napus*) and *R. sativus* tissues were collected when plants were beginning to flower and oats at the milky stage of kernel development (Feekes 11.1). Leaf, stem and root parts of each plant species were separated, freeze dried, ground into a powder and stored at -20°C. The concentration of glucosinolate (GSL) compounds in leaves, stems and roots of the different plant species (except oats) was determined in 300 mg samples of freeze dried tissues using a gradient HPLC method (Dr. J. Kirkegaard, CSIRO Plant Industry Canberra).

The effects of volatile products released from the various tissues on the growth of *V. dahliae*, *C. coccodes*, (both ex soil in QLD and SA), *R. solani* AG3, *Rhizoctonia solani* AG8, *Phytophthora erythroseptica* and *Phytophthora cryptogea* were tested as described for Experiment 1. Radial growth of each culture plate was measured 7 days after hydrating tissues for *R. solani* AG3 and AG8 and 11 days for the other fungi.

Results are presented in Figure 10 and Table 28. All plant tissues, including oats, caused some growth inhibition, although the effects varied with each fungi. Mustard meal was the most toxic and completely inhibited the growth of all fungi at 100 mg tissue. Generally, the *Phytophthora* species were the most sensitive with complete inhibition of growth at 25 mg. *R. solani* was intermediate in sensitivity and *V. dahliae* and *C. coccodes* the least sensitive. The pellet formulation was significantly less toxic to all pathogens, except to *Phytophthora* species, completely inhibiting growth at 25 mg.

**Table 28 Concentration of isothiocyanate liberating glucosinolates in plant tissue and the percentage inhibition of radial growth of potato pathogens exposed to 100 mg of tissue from two *Brassica* species, *R. sativus* and oats**

GSL conc./growth inhibition (%)	<i>B. juncea</i>	<i>B. juncea</i>	<i>B. juncea</i>	<i>B. napus</i>	<i>B. napus</i>	<i>R. sativus</i>	<i>R. sativus</i>	<i>A. sativa</i>	
	Mustard meal	Mustard/ neem pellets	Leaf	Root	leaf	Root	Leaf	Root	leaf
GLS ( $\mu\text{mol g}^{-1}$ )	48	10	38	16	25	36	6	12	-
% growth inhibition									
<i>R. solani</i> AG3	100	34	50	40	44	39	4	2	16
<i>R. solani</i> AG8	100	36	23	28	31	27	9	8	12
<i>V. dahliae</i>	100	27	34	37	33	38	12	14	13
<i>C. coccodes</i>	100	17	52	40	51	43	23	18	14
<i>P. erythroseptica</i>	100	100	50	13	n.t.-	n.t.	0	11	1
<i>P. cryptogea</i>	100	100	55	11	n.t.	n.t.	0	9	0

n.t. not tested

*B. juncea* and *B. napus* leaf tissue was much less inhibitory than mustard meal resulting in 30-60% growth inhibition. Tissues from both species had a similar effect on the radial growth of the fungi. The *Phytophthora* species were the most sensitive, followed by *C. coccodes* and *V. dahliae* and *R. solani* AG8. *R. solani* AG3 was, overall, more sensitive to leaf products than AG8. *R. sativus* leaf tissue was significantly less toxic than *B. juncea* and *B. napus* leaf tissue. Oat tissue caused some inhibition of growth of *C. coccodes*, *V. dahliae* and *R. solani*. Oats do not contain isothiocyanate-liberating glucosinolates but, as the results show, contain other volatile substances that can affect the growth of fungi.

These results are correlated somewhat with the concentration of glucosinolates in the various tissues (Table 28). Indian mustard seed meal had the highest concentration, meal/neem pellets and *R. sativus* the lowest, with intermediate concentrations in *B. juncea* and *B. napus*. When comparing leaf and root tissue, concentrations were lower in the roots than in the leaves of *B. juncea*. For *B. napus* the concentrations in the roots were not greatly different to that in the leaves. Total GSL concentrations were measured here. Recent research has shown that the type, concentration and toxicity of GSLs varies considerably between species, with growing conditions, plant age and between the different parts of the plant itself (Kirkegaard and Sarwar 1998; Sarwar and Kirkegaard 1998; Sarwar *et al.* 1998). Measuring the total concentration of GSLs is only a rough guide to the biofumigation potential of *Brassica* species.

*Experiment 3 – The effects of volatile compounds from herbicide treated an untreated Brassica leaves on the radial growth of fungal pathogens of potatoes*

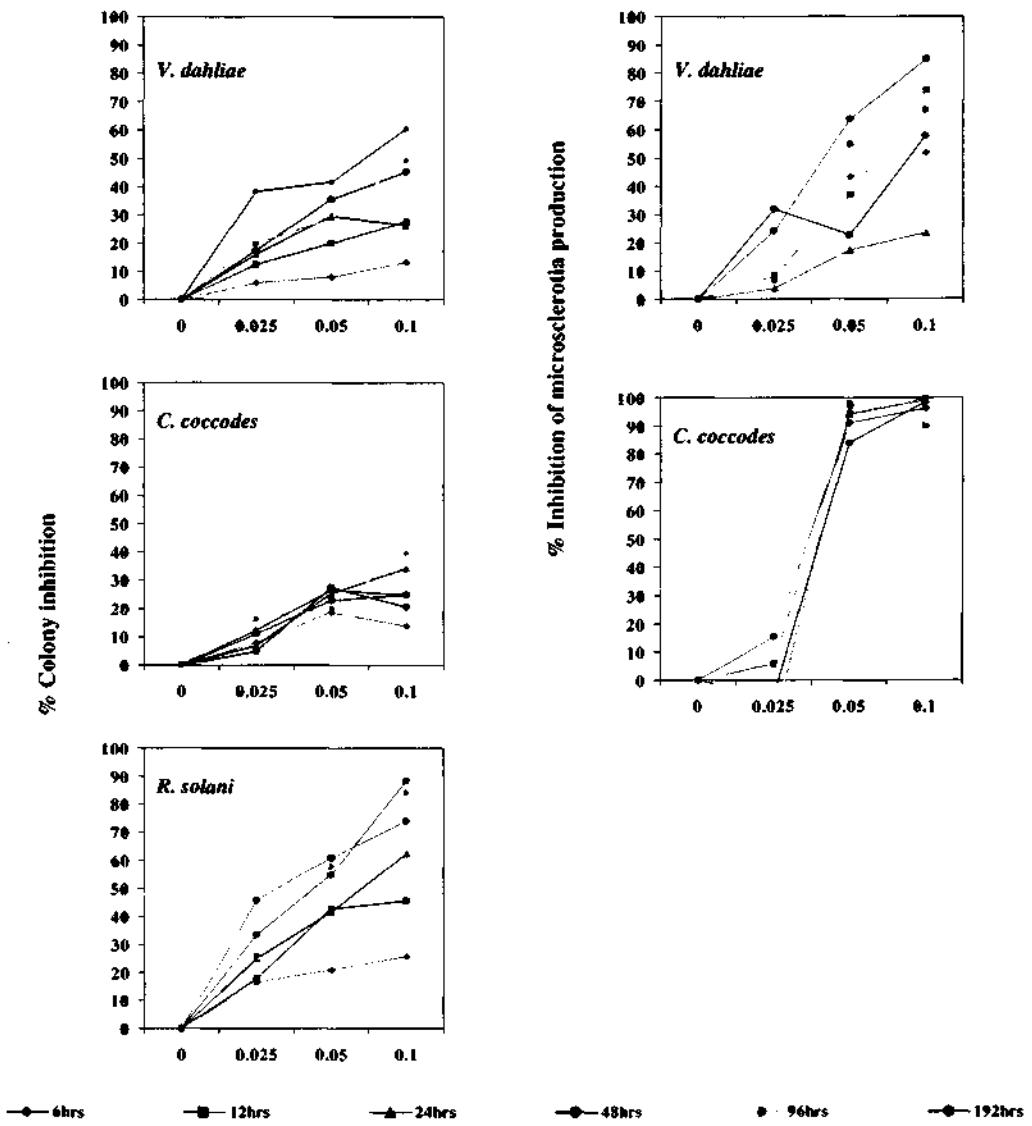
In a variation of Experiment 2, field-grown plants were sprayed with the herbicide Roundup® (360 g/L glyphosate) at 2L/ha and plant material collected and processed as described previously. The aim was to compare the effect of sprayed and unsprayed tissues on fungal growth to determine if herbicides could reduce the biofumigation potential of a *Brassica* crop. Farmers were being encouraged to spray-off *Brassica* crops prior to incorporation into soil. Concentrations of GSL's were measured in the sprayed plants but results were considered unreliable by the chemist and are, therefore not reported here.

Results are presented in Figure 11 and Table 29. Generally, the results demonstrate that 'sprayed' tissues were not as effective in suppressing the growth of the fungal pathogens as the unsprayed tissues. This suggests that the use of herbicides to spray-off crops before incorporation into soil will reduce the biocidal activity of the crop.

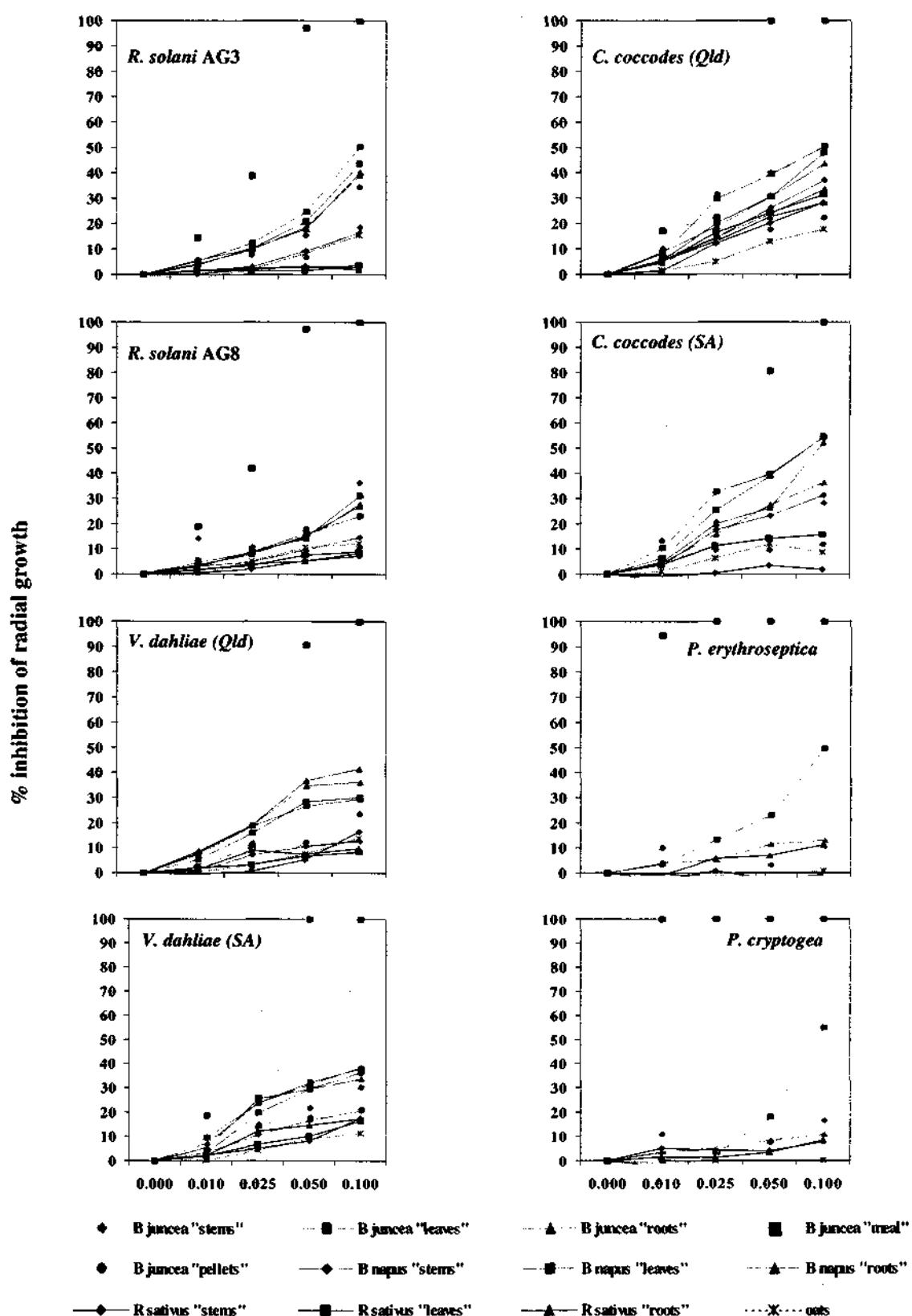
**Table 29 The effects of sprayed (glyphosate treated) and unsprayed leaf tissue (100 mg) of *B. juncea*, *B. napus* and *R. sativus* on the growth of different potato pathogens (Oat leaves were not sprayed)**

Pathogen	Plant species							
	<i>B. juncea</i>		<i>B. napus</i>		<i>R. sativus</i>		<i>A. sativa</i>	L.S.D (P=0.05)
	Un-sprayed	Sprayed	Un-sprayed	Sprayed	Un-sprayed	Sprayed	Un-sprayed	
<i>R. solani</i> AG3	50.3a	7.2d	43.8b	7.2d	3.7de	1.5e	15.6c	4.9
<i>R. solani</i> AG8	23.0b	13.1c	31.2a	4.9d	11.0c	3.0d	12.3c	3.6
<i>V. dahliae</i> (SA)	37.9a	11.6c	36.2a	9.9c	10.5c	16.2b	11.4c	2.7
<i>V. dahliae</i> (Qld)	29.3a	12.0b	30.1a	4.6b	9.6b	8.4b	9.6b	8.5
<i>C. coccodes</i> (SA)	53.8a	12.8c	54.4a	13.4c	15.6bc	27.2b	8.6c	12.6
<i>C. coccodes</i> (Qld)	50.2a	21.2d	47.8b	15.2de	31.4c	14.7e	17.6de	6.5
<i>P. erythroseptica</i>	49.1a	-0.4b	52.1a	8.6b	-1.1b	-1.5b	1.0b	12
<i>P. cryptogea</i>	54.8a	12.4b	56.9a	11.3b	-2.1b	-1.5b	7.8b	9.6

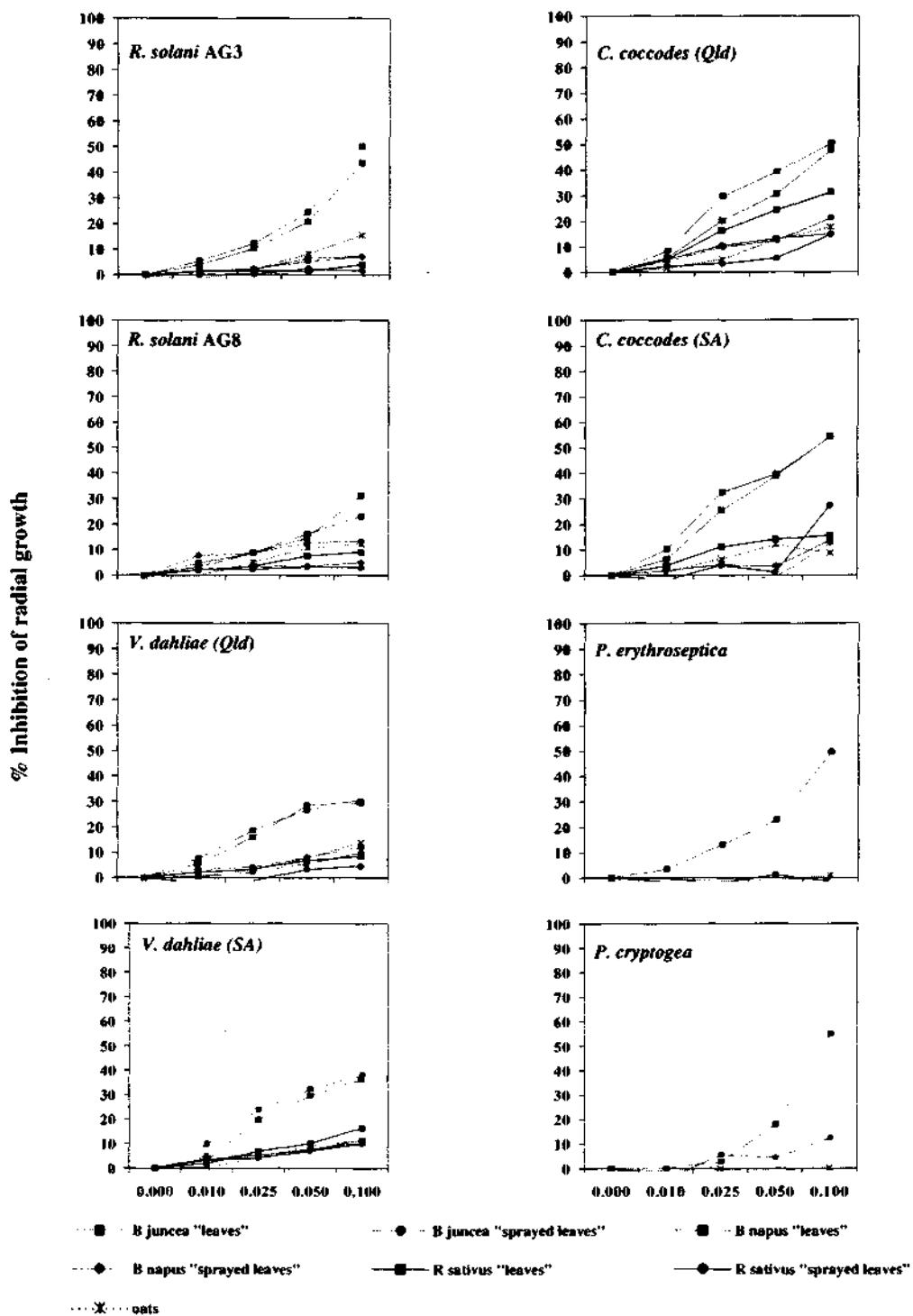
Values followed by the same letters are not statistically different at P=0.05



**Figure 9** The effects of mustard meal on the growth of *Verticillium dahliae*, *Colletotrichum coccodes* and *Rhizoctonia solani* *in vitro*



**Figure 10** The effects of Indian mustard meal, mustard/neem pellets and leaf, stem and root tissue from *B. juncea*, *B. napus*, *Raphanus sativus* and oats on the growth of fungal potato pathogens



**Figure 11** The effects of sprayed (glyphosate treated) and unsprayed leaf tissue of *B. juncea*, *B. napus* and *R. sativus* (0.0, 0.01, 0.025, 0.05 and 0.10 g) on the growth of fungal potato pathogens (Oat leaves were not treated with glyphosate)

#### 4.3.2 The effects of *Brassica* residues, as soil amendments, on diseases of potatoes in the glasshouse and the field

Laboratory and glasshouse studies showed that the Indian mustard seed meal, a by-product of the oil extraction process, was one of the most potent *Brassica* tissues in inhibiting the growth of potato pathogens (Section 4.3.1). Mustard seed meal was evaluated as a soil amendment for the control of potato diseases in a glasshouse experiment and in field experiments in Victoria and South Australia. The aim was to learn more about the potential of biofumigation as a disease management tool and to examine the commercial practicability of mustard meal products for disease control.

##### **Glasshouse trials**

###### *The effects of mustard meal on the growth and disease of potatoes*

A glasshouse study was conducted to determine the effects of Indian mustard meal on the emergence and growth of potato plants (cv. Coliban) and on disease on the progeny potato tubers in a replicated pot trial. The potting media was artificially inoculated with *V. dahliae*, *C. coccodes*, *R. solani* and *P. erythroseptica* and amended with the mustard seed meal at rates equivalent to 1 and 3 t/ha.

Mustard meal at 3 t/ha delayed emergence by up to two weeks and reduced plant growth indicating that the meal was phytotoxic to potato at high rates. The meal at the low and high rate reduced the incidence of tubers with black dot by 80% and 100%, respectively, compared with the untreated control (64% tubers affected). The incidence of black scurf was reduced by 64% in the pots amended with 3 t/ha of meal compared with the control (76% tubers affected). Pink rot did not develop on tubers in pots treated with the high and low rates of meal, although 3% were affected in the untreated control pots. The high rate of meal caused a small reduction in the incidence of tubers with *V. dahliae* in the stem end.

These results confirm *in vitro* studies that mustard meal is inhibitory to plant pathogens but was shown here to be phytotoxic to plants with the potential to reduce emergence, growth and yield at high rates. The results indicate that relatively high rates of meal need to be used to reduce disease incidence and severity.

##### **Field trials**

###### *Toolangi, Victoria, 1997/98*

Defatted Indian mustard seed meal and a mustard/neem pellet formulation were spread over two-row plots (5 m long by 1.63 m wide) and rotary hoed into the top 15 cm of soil in early December, just prior to planting potatoes in a replicated field trial at Toolangi, Victoria in 1997. The site had a history of silver scurf, black dot and powdery scab. Commercial seed tubers and disease-free minitubers (from tissue cultured potato plantlets) were used as untreated controls. The trial was assessed for emergence and degree of stunting seven weeks after emergence. At harvest, numbers and yields of tubers in different size categories in each plot and the incidence and severity of tuber diseases in a 50 tuber sub-sample were recorded. Data was analysed by analysis of variance using Genstat for Windows 5<sup>th</sup> Edition ™ (Lawes Agricultural Trust, Rothamsted Experimental Station).

Mustard meal incorporated into soil at 600 and 1200 kg/ha reduced ( $P \leq 0.05$ ) the proportion of plants emerged by 17% and 51%, respectively, compared with untreated control (Table 30). Both treatments affected the growth of plants as indicated by a higher incidence and severity of stunting ( $P \leq 0.05$ ) than the untreated controls. Mustard pellets had no significant effect on emergence or plant growth.

The progeny of minitubers had symptoms of black dot, silver scurf, powdery scab, common scab and eelworm (root knot nematode) which indicated the presence of soil-borne pathogens (Table 30). There was no evidence of black scurf (*Rhizoctonia solani*). Mustard meal at the highest rate and the mustard pellet treatment resulted in 37% and 25% less ( $P \leq 0.05$ ) tubers with silver scurf than in the untreated controls and the high rate of mustard meal resulted in 59% less ( $P \leq 0.05$ ) tubers with symptoms of eelworm damage. Otherwise, treatments had no significant effect on disease incidence and severity (Table 30).

Mustard meal treatments of 600 and 1200 kg/ha reduced ( $P \leq 0.05$ ) the total yield by 9.9 and 17.1 t/ha respectively and the highest rate reduced ( $P \leq 0.05$ ) the marketable yield by 15.8 t/ha compared with the untreated control (Table 31). The mustard pellet treatment had no significant effect ( $P > 0.05$ ) on the yield.

The highest rate of mustard meal was phytotoxic, affecting plant emergence, growth and yields. The mustard pellet formulation did not have the same effect, probably because they contain less mustard meal at equivalent rates to the meal itself. Generally, mustard meal and pellets did not significantly affect disease incidence and severity. The lower incidence and severity of silver scurf is more likely to be caused by the effect of mustard meal on plant growth. The slower growing plants in the mustard meal plots would have set tubers much later than controls and, as a result, the period of time in which tubers were exposed to inoculum of the silver scurf fungus would have been less than in the controls. The highest rate of mustard meal reduced the incidence of tubers with eelworm damage. It is likely that the meal affected the activity of the eelworm nematodes in soil.

#### *Ballarat and Gerangamete Victoria, 1997/98*

The mustard meal and pellet treatments evaluated at Toolangi were also included in other field trials evaluating the effects of seed and soil treatments on diseases in Victoria in the same season (Horticulture Australia project PT97015). The site near Ballarat in the Central Highlands of Victoria was a volcanic loam (pH 5.2) and the site at Gerangamete, south east of Colac was a sandy loam (pH 5.6). Generally, the mustard meal and mustard/neem pellet treatments did not have a significant effect on plant emergence, growth or the yield of potatoes. The treatments did not affect the incidence and severity of stem and tuber diseases in these trials (Rhizoctonia stem canker, black dot, silver scurf, black scurf and powdery scab) with the exception of black scurf at Gerangamete. Plots treated with mustard meal at 600 and 1200 kg/ha had 43% and 65% less ( $P \leq 0.05$ ) tubers with black scurf than in the untreated controls (19% to tubers affected), respectively. It is possible that the meal had some effect on the fungus, either directly through the release of volatile products or indirectly as an organic soil additive.

#### *Lenswood, Adelaide Hills, South Australia 1999/2000*

Two trials, similar to those previously described, were conducted at Lenswood in the Adelaide Hills, South Australia in which mustard meal was incorporated into soil at rates of 1 and 3 t/ha just prior to planting potatoes. In the first trial, mustard meal at the highest rate

reduced ( $P \leq 0.05$ ) the emergence of potato sprouts by 15% compared with the untreated control, but neither treatment had any significant effect on yield. In the second trial neither treatment affected emergence or yield. Mustard meal treatments did not significantly affect the incidence and severity of skin diseases on progeny tubers (black dot, silver scurf, powdery scab, black scurf, pink rot and *V. dahliae* in the stem end of tubers) in either trial. Plants grown in plots treated with 1 and 3 t/ha mustard meal had higher levels of nitrate nitrogen in petioles 50 days after emergence compared with the controls probably because of the large amounts of organic matter added to the soil.

### *General Discussion*

Laboratory and glasshouse trials showed the potential of Indian mustard meal to control potato pathogens. When incorporated into field soil at various sites, however, mustard meal failed to provide significant disease control. At the higher rates, meal reduced sprout emergence and plant growth, which indicates the production of phytotoxic compounds in soil.

There may be several reasons why these compounds had no effect on disease. Actively growing young plants may be particularly vulnerable to volatile compounds. Soil moisture, pH and organic matter and clay contents may all affect the hydrolysis and decomposition of the meal and this will vary with soil type. The chemicals may be absorbed by the organic and clay fractions of the soil, thereby reducing their concentration. By their very nature, these volatile chemicals may have a very transient life in soil, probably being released into the atmosphere within hours or days. In a glasshouse study, eggplant seedlings were used as a bioassay for the volatile chemicals released from mustard meal in soil. When eggplant seed was planted just after meal was incorporated into a potting media, most failed to germinate. When they were planted 3 days after incorporation, most germinated. This suggests that the volatiles are released as a short-lived pulse soon after hydration.

The relative susceptibility of the different pathogens will depend on their biology. In their dormant states *V. dahliae* and *C. coccodes* occur in soil as sclerotia, *R. solani* as sclerotia and melanised hyphae, *H. solani* as thick walled melanised spores and *S. subterranea* as cystosori. These structures may be less vulnerable to the volatile chemicals than germinating hyphae or, in the case of *S. subterranea*, zoospores. Free living eelworm (*Meloidogyne* spp.) will be exposed to the chemicals and this may explain the reduced incidence of eelworm damage to tubers in the Toolangi trial.

Besides producing ITCs, mustard meal may be biocidal in other ways. The addition of large amounts of fresh organic waste or green manure to soil can liberate ammonia, ammonium, nitrous and nitric acid all of which can be biocidal in high concentrations. This process depends on the material used, soil type, pH and soil organic matter content. The incorporation of certain organic waste products to soil has been shown to control some potato pathogens (George Lazarovits personal communication).

**Table 30 The effects of different rates of mustard seed meal and pellet formulations incorporated into soil pre-planting on the emergence, growth (stunting) and the incidence and severity of diseases of potato tubers in a field trial, Toolangi, Victoria 1997/98**

Treatment	Post emergence				Tuber disease assessment								
	Emergence (%)		Stunting		Black dot		Silver scurf		Powdery scab		Common scab		Eel worm
	Incidence (%)	Severity (0-3)	Incidence (%)	Severity (0-4)	Incidence (%)	Severity (0-4)	Incidence (%)	Severity (0-4)	Incidence (%)	Severity (0-4)	Incidence (%)	Severity (0-4)	Incidence (%)
Control	99.2	38.0	0.63	1.67	0.03	95.0	2.15	24.7	0.40	80.2	1.70	59.3	0.93
Minitubers	72.0	67.0	1.85	0.33	0.003	81.5	1.37	3.2	0.04	74.2	1.14	32.5	2.53
Mustard Meal 600	82.3	61.0	1.33	2.17	0.04	85.7	1.46	23.0	0.31	81.0	1.48	45.4	0.73
Mustard Meal 1200	49.0	72.0	2.33	5.33	0.09	60.0	0.94	39.2	0.84	67.2	1.12	24.2	0.28
Mustard Pellets 1000	95.5	54.0	0.80	6.50	0.09	70.7	1.29	33.2	0.70	79.5	1.28	41.8	0.55
F-test P value	<0.001	0.01	<0.001	0.22	0.34	<0.001	<0.001	0.35	0.30	0.23	0.26	0.017	0.5
I.s.d. (P<0.05)	10.26	17.97	0.49	5.51	0.09	11.51	0.47	33.24	0.73	12.96	0.55	18.93	2.50

**Table 31 The effects of different rates of mustard seed meal and pellet formulations incorporated into soil pre-planting on total and marketable yield and on yield and number of tubers in different size categories in a field trial, Toolangi, Victoria 1997/98**

Treatment	Total yield (t/ha)	Marketable yield (t/ha)	Yield of misshapen tubers (t/ha)	Total yield in different size categories							
				<75g				75-280g			
				No.tubers/plot	Weight (t/ha)	No.tubers/plot	Weight (t/ha)	No.tubers/plot	Weight (t/ha)	No.tubers/plot	Weight (t/ha)
Control	79.9	49.05	1.33	27.2	1.90	90.3	24.24	47.3	25.55	30.7	28.2
Minitubers	48.6	35.00	0.37	25.5	1.67	75.5	19.11	29.7	16.14	13.8	11.7
Mustard Meal 600	70.0	45.88	1.37	27.5	1.86	88.2	23.59	42.2	22.85	21.7	21.7
Mustard Meal 1200	62.8	33.21	1.50	19.0	1.26	61.5	15.31	34.2	18.67	29.5	27.6
Mustard Pellets 1000	76.7	51.71	1.77	27.2	1.73	97.0	26.54	49.7	26.50	23.7	21.9
F-test	<0.001	<0.001	0.07	0.19	0.26	<0.001	<0.001	<0.001	<0.001	0.02	0.03
I.s.d. (P<0.05)	9.51	5.84	1.14	8.83	0.61	18.03	4.09	7.65	4.45	10.17	10.49

#### 4.3.3 The effects of *Brassica* crops grown before potatoes on diseases of potatoes in the field

The results of field trials in which various species and varieties of *Brassica* were ploughed-in as green manures prior to cropping potatoes are described in Section 4.2. Although there is evidence from laboratory trials demonstrating the potential of *Brassica* to inhibit potato pathogens, there were no apparent effects of *Brassica* crops on disease and yield at four trial sites over two or more seasons.

The concept of biofumigation has caught grower's imagination and there is an assumption that ploughing-in a *Brassica* crop before potatoes will result in dramatic reductions in disease in the potato crop. However, there are many complicating factors at play that can influence the result. They include soil type (physical structure, pH, chemistry,), soil conditions (moisture, temperature, organic matter content), type of pathogen, whether the *Brassica* is a host of the target pathogen, the amount of biomass produced by the *Brassica*, the type of ITC's produced and their concentrations in the plant.

Soil condition is an important factor affecting the efficacy of ITC's. For effective fumigation with the commercially manufactured ITC, Metham sodium, soil must be worked to a fine tilth, have a relatively low organic matter content and must be relatively warm and moist. This fumigant is more effective in sandy soil than in heavier soils. For clay loams with high organic matter contents, higher rates of application are required. The effectiveness of volatile compounds released from decaying *Brassica* residues may also be governed by these factors. The concentration of ITC's released in soil when *Brassica* residues are ploughed-in may only be one tenth of that from commercial fumigation with Metham sodium (J Nichols personal communication).

There is good evidence that ITC's in *Brassica* crops such as Indian mustard and canola suppress the take all fungus in soil (Kirkegaard *et al.* 1998) resulting in more effective control of the disease in the subsequent wheat crop than with other 'break' crops that do not have ITC's. This is one of the few examples of biofumigation in practice in the field. The take-all fungus is particularly sensitive to ITC's (Angus *et al.* 1994; Kirkegaard *et al.* 1998). It has a very narrow host range surviving in the debris of grasses and cereals and has limited ability as a saprophyte in soil. The fungus is a particularly good candidate for control with break crops, particularly with *Brassica*. Other pathogens may not be good candidates for control. *R. solani*, for example, occurs in soil as thick walled melanised hyphae and sclerotia. It is a good saprophyte, readily colonising organic debris and plant roots. The actively growing hyphae are likely to be the most vulnerable to biocides than the dormant forms of the fungus. *C. coccodes* and *V. dahliae* also survive as sclerotia and *H. solani* as melanised spores and *S. subterranea* as cystsori and may be also be less vulnerable to ITC's. More research needs to be done to determine the effect of ITC's on the dormant forms of these pathogens in soil.

The use of *Brassica* is complicated by the fact that they can host potato pathogens. *R. solani* AG3, for example, actively colonised *Brassica* roots in field plots in our trials and readily formed sclerotia in an epiphytic relationship with the plant. *Brassica* are also good hosts of the root knot (*Meloidogyne* spp.) and root lesion nematodes (*Pratylenchus* spp.). Although *Pratylenchus* is sensitive to some of the ITC's produced by *Brassica* *in vitro* (Potter *et al.* 1998), some *Brassica* species are more resistant to attack by the nematode than others, depending on which ITC's are present in the roots (Potter *et al.* 1999).

There is anecdotal evidence that growing *Brassica* before potatoes reduces the quality of the tubers. Field officers for McCain Foods have noticed that potatoes grown after *Brassica* are 'rougher', being of poorer quality than those grown after pasture for instance. *Brassica* crops may possibly have a detrimental effect on soil structure and nutrients, or may in fact increase populations of some pathogens that affect tuber quality, such as *R. solani*.

Whilst the focus with *Brassica* has been on disease suppression from ITC's, ploughing-in green manures crop can cause disease suppression in other ways. The decay of large amounts of organic material high in nitrogen can release various acids as part of the nitrogen cycle which are toxic to plant pathogens in high concentrations. This process depends on the soil temperature, moisture and pH. Green manuring can also encourage populations of soil micro organisms which suppress pathogen activity through competition.

Current research on biofumigants is focused on determining the ITC profiles of the different *Brassica* species and varieties and on the relative toxicities of these chemicals and their behaviour in the soil profile. Field studies should include measurements of biomass, ITC concentrations in soil after incorporation, effects on incorporation on soil nutrients and microbial populations and effects on pathogen populations, as well as measurements of effects on disease and yield.

#### **4.4 *Rhizoctonia solani* in potato cropping systems in Victoria, Australia**

##### **Summary**

The results of systematic field surveys and rotation trials showed that *Rhizoctonia* canker and black scurf are major diseases of potato in Victoria. *Rhizoctonia solani* was systematically isolated from typical stem and stolon cankers on young plants, from sclerotia on tubers and from the roots of pasture and *Brassica* species grown in rotation with potatoes in field trials in Victoria. Of 46 isolates taken from cankers, 67% belonged to anastomosis group (AG) 3 and 26% to AG2 (23% AG2-1, 2% AG2-2). Of 206 isolates taken from sclerotia on progeny tubers (one sclerotium/tuber), 68%, 12%, 2%, 2%, and 3% belonged to AG3, AG2-1, AG2-2, AG4 and AG5, respectively. Of 48 isolates from sclerotia on commercial seed tubers from various sources, 92% belonged to AG3 and 4% to AG2-1. Sclerotia sampled from the tap-roots of clover and fodder *Brassica* species grown in rotation with potatoes belonged to both AG3 and AG2.

Most of the 41 isolates (81%) taken from stems and tubers, affected by an undescribed disease attributed to *R. solani*, belonged to AG2 (16 AG2-1, 19 AG2-2). Symptoms included a girdling necrosis ('wire-stem') of stems just below the soil line, cankers on tubers and rapid wilting and death of plants in mature crops during prolonged periods of hot weather.

In a series of glasshouse pathogenicity tests, isolates of *R. solani* AG2-1 and AG2-2 caused cankers on the stems and stolons of potato plants similar to those caused by AG3. The pathogenicity of the AG2 isolates varied considerably ranging from slightly to highly pathogenic to stems and stolons compared with AG3 isolates which were moderately to highly pathogenic. AG2 isolates also caused tubers to be misshapen and caused cankers on tubers. In contrast to AG3 isolates, which all produced significant numbers of relatively large sclerotia on tubers, AG2 isolates produced, few, if any, relatively small sclerotia on tubers.

In a pathogenicity test with other plant species, *R. solani* AG3 was only mildly pathogenic to fodder *Brassica*, and red clover and non pathogenic to Indian mustard, but formed abundant sclerotia on the roots of all three species. *R. solani* AG2-1 isolates were pathogenic to the three species causing damping-off and 'wiresstem' symptoms. The AG2-1 isolates also formed sclerotia in the roots of the fodder *Brassica* and Indian mustard, but not in the roots of red clover where the fungus was evident only as hyphae.

These studies show that although *R. solani* AG3, the 'potato strain' is the most common group in potato production systems in Victoria, *R. solani* AG2 is also relatively common and capable of causing significant disease in potatoes. These studies also show that AG3 can form a non-symptomatic relationship with other crop species grown in rotation with potato.

##### **Introduction**

Stem canker and black scurf caused by the fungus *Rhizoctonia solani*, are major diseases of potatoes worldwide. They are also common and widespread in Australia affecting both yield and quality of potatoes. For example, a systematic survey of Russet Burbank crops in the Central Highlands area of Victoria during the 1996/97 season (Section 4.1) found stem canker in all of 16 crops sampled, with disease incidence averaging between 1-76% of plants

affected. The black scurf symptom (sclerotia on the tuber skin) was found on tubers in 12 of the 16 crops sampled, with as much as 38% of tubers affected in some crops.

*Rhizoctonia solani* is a heterogeneous species of the *Rhizoctonia* genus affecting a very wide host range. The species is divided into 13 subspecific groups called anastomosis groups (AG) (Carling *et al.* 2002; 1991) based on somatic (vegetative) incompatibility responses between hyphae of genetically distinct isolates (anastomosis reactions) (Carling *et al.* 1988). Each AG may have a high degree of host specificity. AG3, for example, is most commonly isolated from potatoes and AG8 from cereal roots (Banville *et al.* 1996).

Of the 13 anastomosis groups of *R. solani*, six have been associated with potatoes. They include AG1, AG2 (subgroups 2-1 and 2-2), AG3, AG4, AG5 and AG9 (Banville *et al.* 1996). Traditionally, AG3 has been known as the potato attacking strain, being host-specific to potatoes. However, AG4 and AG5 are also capable of damaging potato plants. Most of the sclerotia isolated from potato tubers are reported to belong to AG3 (Banville *et al.* 1996).

Damage to potatoes by *R. solani* is likely to involve a complex of different AG groups. This has implications for crop rotation. There is only one reported study of *R. solani* in potatoes in Australia. Balali *et al.* (1995) collected isolates of the fungus from stems, roots, tubers and soil in potato crops grown in Virginia and Lenswood in South Australia. Of 301 isolates tested, 90% were AG3 and 7% and 2% were AG4 and AG5, respectively. A study in Canada showed that the relative proportions of AG's isolated from potato plants can vary with different rotations (Gudmestad *et al.* 1989). In order to understand the relationship between *R. solani* and rotation, it is essential that we identify the different groups of the fungus in the major potato cropping systems and how they interact with the rotation crops. Without a good understanding of the pathogen, its life-cycle, ecology and disease epidemiology, it is difficult to develop effective management strategies.

This section reports on the isolation, characterisation and pathogenicity of *R. solani* from potatoes and other crops grown in rotation with potatoes in two main cropping areas of Victoria, namely the Central Highlands and the Colac region. A new disease of potatoes attributed to *Rhizoctonia solani* is also described.

#### 4.4.1 Collection, isolation and characterisation of *Rhizoctonia solani* from potatoes and other plant species

##### Sampling

Trial plots of potatoes, or other plant species in rotation with potatoes, were systematically sampled during the 1996/97-2000/2001 seasons. Trial plots planted to potato were sampled early in the season, about 6-8 weeks after planting, when classic symptoms of Rhizoctonia cankers are apparent on the subterranean parts of emerged sprouts and stolons. Potato tubers were sampled at harvest time after the crop had died-off. Other plant species were sampled in early spring, early summer or mid summer, depending on the species and their role in the rotation. The different scenarios from which samples were taken are described below.

##### Rotation trial plots

Samples were taken from rotation trials in the Central Highlands of Victoria at Bullarook described in Section 4.2.3 and at Clarkes Hill (see Section 4.5.1). In potato plots, 8 plants

were sampled, four from the 2<sup>nd</sup> row and 4 from the 5<sup>th</sup> row (8-row plots). Tubers with the black scurf symptom were taken from a random sample of 50 tubers harvested from the 3<sup>rd</sup> and 4<sup>th</sup> rows of each plot for disease assessments. Isolations were done from a 10-tuber sub sample. The non-potato plots sampled are listed in Table 33.

A total of 10 plants were collected along a diagonal transect across each plot.

#### ***Chemical treatment trial plots***

Trial plots for the evaluation of the effects of seed and soil treatments on *Rhizoctonia* and other diseases of potatoes (PT97015) at Clarks Hill in the Central Highlands and at Gerangamete, south east of Colac were also sampled. A total of six plants were sampled systematically from each two-row by 5m plot (three from each plot row) from untreated control plots of commercial seed and mini-tubers about six to eight weeks after planting. A sub sample of 10 tubers with black scurf was taken from a 50-tuber sample taken from each two-row plot at harvest time.

#### **Isolation of *R. solani* from plant tissue**

Plant samples taken from trial plots were lightly washed to remove soil. Specimens were examined by the naked eye or under a dissecting microscope for typical symptoms of damage caused *R. solani* and for the presence of fungal hyphae and sclerotia on the subterranean parts of crowns, stems, stolons, roots and tubers. Fragments of diseased tissue or clumps of hyphae were excised from plant specimens, washed through three consecutive rinses of sterile distilled water and plated onto 2% water agar containing 25 ppm tetracycline hydrochloride and incubated at room temperature. Hyphal tips of *R. solani* were excised after 24 hrs and grown-on on potato dextrose agar (PDA). Cultures were maintained on full strength PDA and stored on 10% PDA at 4°C.

For grass, wheat and buckwheat roots, which had no apparent symptoms of damage consistent with that caused by *R. solani*, nor evidence of the fungus itself on the root systems, ten, 5-10mm segments of roots were taken at random and treated and plated as described previously.

Sclerotia (one sclerotia/tuber) were excised from potato tubers or diseased stems and roots, surface sterilised in NaOCl (1% available Cl), washed through three consecutive rinses of sterile distilled water and plated onto 2% water agar containing 25 ppm tetracycline hydrochloride and incubated at room temperature. Hyphal tips from germinating sclerotia were excised after 12 hrs and grown-on on PDA as described previously.

#### **Characterisation of *Rhizoctonia solani***

##### ***Nuclei number per cell***

The number of nuclei per cell was determined using the nuclei stain Safranin-O as described by Bandoni (1979). All multinucleate isolates that were characteristic of *R. solani* were further characterised by anastomosis grouping.

##### ***Anastomosis grouping***

Multinucleate isolates of *Rhizoctonia solani* were further characterised by anastomosis grouping using the method of Parmeter *et al.* (1969) with the tester isolates AG2-1, 2-2, 3, 4,

5 (Table 32). A disc (4mm diameter) of mycelium from a tester isolate and from an unknown culture were placed at opposite edges of a cellophane rectangle in the centre of a Petri dish containing 1.5% water agar. Hypha-hypha interactions between the two cultures where hyphae of the two isolates met in the centre of the cellophane were viewed at  $\times 400$  magnification and categorised using the method of Carling *et al.* (1988).

**Table 32. Tester isolates used for anastomosis grouping of Victorian isolates of *R. solani***

AG tester	Isolate No.	Accession	Location/Origin
AG 1-IC	n.a.	M 43	Unknown
AG 2-1 <sup>A</sup>	ATCC 76168	PS-4	Japan
AG 2-1 <sup>A</sup>	n.a.	21RC02	South Australia
AG 2-2 <sup>A</sup>	76125	RI-64	Japan
AG 3 <sup>A</sup>	ATCC 76167	ST-11-6	Japan
AG 4 <sup>A</sup>	ATCC 76127	Rh-165	Japan
AG 5 <sup>A</sup>	ATCC 76128	GM-10	Japan
AG 6	n.a.	OT 2-1	Japan
AG 8	1334	n.a.	South Australia
AG 9	n.a.	BS 24	n.a.
AG 10	n.a.	R 369	n.a.
AG 11	n.a.	ROTH 26	n.a.

<sup>A</sup>Testers used to characterise isolates taken from trial plots. All testers were used to characterise isolates taken from crops affected by 'Rhizoctonia wilt'.

n.a. Not available at the time of writing

## Results

More than 300 isolates of *R. solani* were collected. The anastomosis grouping of the isolates taken from potatoes and other plant species is summarised in Table 34.

### *Rhizoctonia canker and black scurf on potatoes*

The fungus *Rhizoctonia solani* was isolated from typical symptoms of canker on the stems and stolons of young potato plants and from sclerotia on mature progeny tubers sampled from field trial plots in the two different regions in Victoria.

Of 46 isolates taken from typical Rhizoctonia cankers on stems and stolons of young plants, 31 (67%) belonged to AG3 and 12 (26%) to AG2 (11 to AG2-1 and 1 to AG2-2). Of 208 isolates taken from sclerotia on progeny tubers (one sclerotium per tuber) 141, 24, 5, 4 and 7 belonged to AG3, AG2-1, AG2-2, AG4 and AG5, respectively (68%, 12%, 2.4%, 1.9%, 3.4%, respectively). Of 48 isolates from sclerotia on commercial seed tubers from various sources, 44 (92%) belonged to AG3 and 2 to AG2-1.

### *Other plant species*

Evidence of *R. solani* on the root systems of plant species other than potato is presented in Table 33. Abundant sclerotia and hyphae, characteristic of *R. solani*, were found on the main roots of 'Hobson' and 'Striker' fodder rape grown in rotation plots. The roots of the fodder rapes appeared healthy with no obvious symptoms of damage caused by the fungus, whereas occasional lesions were apparent on the roots of Indian mustard and 'BQ Mulch®'. *R. solani* grew consistently from the hyphae and sclerotia and from fragments of root lesions. The

fungus was also isolated from lesions on the roots of red clover and hyphae from clover roots were also identified as *R. solani*. A binucleate *Rhizoctonia* (*R. cerealis*) was frequently isolated from grass and wheat roots. *R. solani*-like hyphae or sclerotia were not apparent on the roots of perennial ryegrass, wheat and buckwheat, nor was the fungus isolated from root fragments of these species that were plated onto agar.

Sclerotia on the roots of 'Hobson' and 'Striker' fodder rapes from rotation plots were identified as *R. solani* AG3 and AG2-1, whereas *R. solani* from hyphae and lesions on *Brassica* roots and red clover roots belonged to AG2-1.

**Table 33. *Rhizoctonia solani* on different plant species and cultivars rotated with potato in rotation trials.**

Species and cultivar	Evidence of <i>R. solani</i> on roots	<i>R. solani</i> in culture
Fodder rape <i>Brassica napus</i> L. cv. Hobson	Hyphae, sclerotia	+
Fodder rape <i>Brassica napus</i> L. cv. Striker	Hyphae, sclerotia	+
Fodder rape mixture: <i>Brassica napus</i> L. & <i>Brassica campestris</i> L. 'BQ Mulch®'	Root lesions <sup>A</sup> , hyphae	+
Indian Mustard <i>Brassica juncea</i> L. (Czern.) cv. Nemfix®	Root lesions <sup>A</sup> , hyphae	+
Red clover <i>Trifolium pratense</i> L. cv. Cowgrass	Root lesions <sup>A</sup> , hyphae	+
Buck wheat <i>Fagopyrum esculentum</i> (Moench.) cv. Manor	No	-
Wheat <i>Triticum aestivum</i> L. cv. Temora	No	<sup>B</sup>
Perennial ryegrass <i>Lolium perenne</i> L. cv. Ellett	No	<sup>B</sup>

<sup>A</sup> Occasional Rhizoctonia-like cankers on main roots

<sup>B</sup> Binucleate *Rhizoctonia cerealis* isolated

**Table 34. Anastomosis grouping of isolates of *Rhizoctonia solani* collected from subterranean parts of potato plants, other plant species and organic debris from trial sites and diseased crops in Victoria**

Source	No. tested	AG3	AG2-1	AG2-2	AG4	AG5	Others (no reactions with testers <sup>A</sup> )
<b><i>Rhizoctonia</i> canker and black scurf</b>							
Stem canker	46	31	11	1	0	0	3
Sclerotia - progeny tubers	208	141	24	5	4	7	27
Sclerotia - seed tubers	48	44	2	0	0	0	2
	302	216	37	6	4	7	32
<b>Rotation crops</b>							
Brassica roots - lesions and hyphae	7	0	2	0	0	0	5
Brassica roots - sclerotia	6	4	2	0	0	0	0
Clover roots - lesions and hyphae	5	0	4	0	0	0	1
	18	4	8	0	0	0	6
<b>Total</b>	<b>320</b>	<b>224</b>	<b>53</b>	<b>6</b>	<b>4</b>	<b>7</b>	<b>38</b>

<sup>A</sup> Testers used were AG2-1, AG2-2, AG3, AG4, AG5

## Discussion

In this study, over two thirds of the isolates taken from stem cankers on potato plants were identified as belonging to the anastomosis group AG3. This is consistent with other studies on *Rhizoctonia* in potato around the world (Banville *et al.* 1996). However, a relatively high proportion (26%) of isolates taken from stem cankers were AG2 (mostly AG2-1), which is significantly higher than reported by others (Chand and Logan 1983; Chang and Tu 1980). *Rhizoctonia solani* AG2 was not isolated from potatoes in the only other study of *R. solani* in potato crops in Australia (Balali *et al.* 1995). This suggests that AG2s could play a more important role in the Rhizoctonia disease complex of potato crops in Victoria than elsewhere. A small proportion of isolates found in Victoria were AG4 and AG5. Balali *et al.* (1995) also reported small numbers of AG4 and AG5 in potato crops at Virginia in South Australia and both groups are often found in potato crops around the world (Banville *et al.* 1996).

The majority of isolates taken from sclerotia on tubers belonged to AG3 which is consistent with other reports (Banville *et al.* 1996). Only a small proportion were found to be AG2 which suggests that AG3 is the main source of seed-borne inoculum of *R. solani*.

The potato strain of *R. solani*, AG3, was frequently isolated from the roots of *Brassica* species, sometimes from lesions on roots, but more frequently from hyphae and sclerotia growing on healthy roots. The presence of abundant sclerotia of AG3 on the roots of fodder rape shows that *R. solani* can form a non-symptomatic relationship plant with species other than potato. Carling *et al.* (1986) reported that *R. solani* AG3 formed an epiphytic, rather than a pathogenic interaction with most of 27 plant species from 26 genera tested in a glasshouse study. The fungus appears to use the roots as a substrate in much the same way as potato tubers. This has implications for the management of the fungus in rotations.

AG2s are often associated with the Leguminosae, Cruciferae, Chenopodiaceae (most sugar beets) or Graminae (Ogoshi A 1987). The relatively high proportions of AG2 in the Victorian production systems studied here may be due to a reliance on long-term pastures of grass and fodder legumes (clovers) in potato production systems and frequent use of a crop of fodder *Brassicas* species to fatten livestock after potatoes. Further studies are needed to determine the pathogenicity of the AG2 isolates and to determine the relative importance of AG3 and AG2 in the Rhizoctonia disease complex described here.

### 4.4.2 The pathogenicity of isolates of *Rhizoctonia solani* from potatoes to potato and other plant species in glasshouse tests

A series of glasshouse pathogenicity tests were conducted to compare the pathogenicity of different isolates of *R. solani* AG3 and AG2 to potatoes and other species grown in rotation with potatoes. *R. solani* AG2s (subgroups 1 and 2) have been reported to be associated with potatoes (Chand and Logan 1983; Chang and Tu 1980) but are usually described as weak pathogens of potatoes. However, our experience indicated that the isolates of AG2s taken from Victorian potato crops could be very pathogenic to potatoes.

**Experiment 1 - The pathogenicity of potato isolates of *Rhizoctonia solani* AG3 and AG2 to potatoes and other plant species grown in rotation with potatoes**

### Introduction

Symptoms of stem canker and black scurf on potatoes are usually attributed to *Rhizoctonia solani* AG3 (Banville *et al.* 1996). However, groups AG1, 2, 4, 5 and 9 have also been isolated from potatoes (Banville *et al.* 1996). Only the groups AG3, 4 and 5 were isolated from potato plants and soil at Virginia and Lenswood, South Australia in the only reported Australian study of AG groups in potatoes (Balali *et al.* 1995). In this study, 90% of the isolates collected belonged to AG3.

In a study of *Rhizoctonia* in potato crops in Victoria (Section 4.4.1), 26% of isolates of *R. solani* taken from stem cankers on potato plants were found to be AG2 (24% AG2-1, 2% AG2-2) and 67% AG3. Furthermore, isolates of AG3 were frequently found as sclerotia on the roots of fodder rape (*Brassica napus* L.) and Indian mustard (*Brassica juncea* L. Czern. & Coss.). *Rhizoctonia solani* AG2-1 is commonly associated with *Brassica* and leguminous crops (Khangura *et al.* 1999; Hwong *et al.* 1996; Wong and Sivasithamparam 1985). Both fodder rape and fodder legumes are grown in traditional pasture-potato rotation systems in Victoria and this may explain the relatively high incidence of AG2. A glasshouse study was conducted to compare the pathogenicity of isolates of potato isolates of *R. solani* AG2-1 and AG3 against potato and three crop species grown in rotation with potato.

### Materials and Methods

Inocula of three isolates of *R. solani* (AG3 and AG2-1 from sclerotia on potato tubers and an AG2-1 from stem canker on potato plants) were prepared by growing isolates on sterile French white millet seed according to the method of McDonald and Rovira (1985). Millet inoculum was incorporated into a sand-based potting media in 15-cm diameter black plastic pots (16 propagules/kg potting medium). Pots were planted with a single potato minituber derived from tissue-cultured plantlets (cv. Sebago) or sown with the seed (6/pot) of fodder rape (*B. napus*, cv. Hobson), Indian mustard (*B. juncea*, cv. Nemfix®) or red clover (*Trifolium pratense* L., cv. Cowgrass). Control treatments were prepared using sterile millet seeds. The pots were arranged on glasshouse benches in a randomised complete block design with four replications. Glasshouse temperatures were maintained at 15°C night and 25°C day and pots were watered to saturation twice daily.

All treatments were harvested and assessed at two different stages, first when potatoes were at early tuber set and the second when potato plants had senesced. At the latter stage, the Indian mustard had flowered, whereas the fodder rape and clover had not. The incidence and severity of stem canker, hypocotyl rot, crown rot, production of sclerotia and the abundance of hyphae on root systems were recorded. Rating scales for the assessment of disease severity are described in Table 35.

### Results

In this study, the three isolates of *R. solani* were associated with damage to the stems of potato plants and hypocotyls or crowns of *Brassica* and red clover and with the production of sclerotia on tubers and roots. However, they did not damage roots. Pathogenicity varied with plant species and isolate.

All three isolates of *R. solani* were pathogenic to potatoes causing symptoms of stem canker on underground potato stems and stolons and black scurf on tubers (Table 35). The incidence and severity of stem canker caused by the isolate "AG2-1 Stem" was comparable to that caused by the AG3 isolate, whereas the "AG2-1 Sclerotia" isolate caused a relatively low incidence and severity of the disease. All of the progeny tubers grown with the AG3 isolate had symptoms of black scurf, compared with only 12.8% and 17%, respectively, of tubers grown with the sclerotia and stem isolates of AG2-1.

The three isolates caused damping-off and wire-stem symptoms on fodder rape (Table 35). The "AG2-1 Stem" isolate was the most pathogenic, resulting in 95% of plants affected compared with 18.8% and 9% of plants affected by the isolates "AG2-1 Sclerotia" and the AG3, respectively. All isolates produced sclerotia on root systems of fodder rape, with the AG3 isolate producing the most abundant sclerotia and the "AG2-1 Stem" isolate the least abundant sclerotia.

The "AG2-1 Stem" isolate caused hypocotyl rot or "wire-stem" symptoms on 100% of the Indian mustard seedlings but did not produce sclerotia on roots (Table 35). In contrast, the AG3 and the "AG2-1 Sclerotia" isolates did not damage the hypocotyls of Indian mustard seedling but produced abundant sclerotia on roots.

All isolates caused symptoms of hypocotyl rot or crown rot on red clover seedlings and caused damping-off (Table 35). No isolate produced sclerotia on the roots of clover. However, abundant hyphae of *R. solani* were observed on crowns of red clover plants grown with each different isolate.

## Discussion

This study shows the potential of *R. solani* AG2-1 to cause significant damage to potato stems. Other studies have reported AG2's to be only mildly pathogenic or non-pathogenic to potatoes (Carling and Leiner 1986; Chand and Logan 1983). In contrast to the AG3 isolate, the AG2-1 isolates produced only a small number of sclerotia on potato tubers. These results have implications for the management of Rhizoctonia stem canker and black scurf in potatoes.

AG2-1 is commonly associated with damage to species of *Brassica* (Hwong *et al.* 1996; Khangura *et al.* 1999). In this study, one isolate of AG2-1 from potatoes caused significant damage to the stems of both fodder rape and Indian mustard but the second isolate, also from potatoes, was not pathogenic to Indian mustard.

Although the isolates of AG3 and AG2-1 in this study did not appear to be highly pathogenic to red clover, they did grow epiphytically on the roots of this fodder legume. This suggests that clover could potentially act as a substrate for *R. solani* in potato production systems.

The AG3 isolate was not significantly pathogenic to the two *Brassica* species but produced an abundance of sclerotia on roots. This confirms observations from field plots where sclerotia of AG3 were found on the roots of fodder rape (Section 4.4.1). This suggests that the roots of *Brassica* species can act as a substrate for *R. solani*, thereby supporting populations of the fungus in potato production systems.

This study shows that Rhizoctonia diseases of potatoes in typical pasture-potato production systems in Victoria may involve *R. solani* AG 2-1, as well as the potato specific AG 3.

Further studies on the ecology of *R. solani* are needed to determine the relative importance of the different AG groups in the Rhizoctonia disease complex in potatoes.

**Table 35. Pathogenicity of potato isolates of *Rhizoctonia solani* AG 3 and AG 2-1 to four different plant species in a glasshouse experiment**

(Stem canker or hypocotyl rot was assessed on seedlings when potatoes were at early tuber set and the incidence and abundance of sclerotia was assessed on mature plants after potato plants had senesced).

Host	“AG 3 Sclerotia”				“AG 2-1 Sclerotia”				“AG 2-1 Stem”			
	Stem canker/hypocotyl rot		Sclerotia		Stem canker/hypocotyl rot		Sclerotia		Stem canker/hypocotyl rot		Sclerotia	
	Inc. <sup>A</sup>	Sev. <sup>B</sup>	Inc. <sup>A</sup>	No./tuber or root system	Inc. <sup>A</sup>	Sev. <sup>B</sup>	Inc. <sup>A</sup>	No./tuber or root system	Inc. <sup>A</sup>	Sev. <sup>B</sup>	Inc. <sup>A</sup>	No./tuber or root system
Potato	65.0	3.0	100.0	14.3	16.7	1.5	12.8	1.3	71.0	3.5	17.0	0.4
Fodder rape	9.0	0.1	83.0	5.7	18.8	0.2	44.0	1.8	95.0	2.1	20.0	0.4
Indian mustard	0.0	0.0	100.0	6.5	0.0	0.0	60.0	4.1	100.0	3.0	0.0	0.0
Red clover	62.5	1.3	84.0 <sup>D</sup>	0.0	65.6	0.7	55.0 <sup>D</sup>	0.0	69.7	1.9	96.0 <sup>D</sup>	0.0

<sup>A</sup>Inc. – Incidence: % of plants affected

<sup>B</sup>Sev. – Severity rating on scale of 0-5: 0, healthy; 1, <25%; 2, between 25-50%; 3, between 50-75%; 4, >75% of stem or stolon surface with lesions; 5, dead moribund

<sup>C</sup>Stem canker on potato stems, hypocotyl rot on fodder rape, Indian mustard and red clover

<sup>D</sup>Inc. – Incidence: % plants with *R. solani* hyphae on root system

## **Experiment 2 - A comparison of the pathogenicity of isolates of *Rhizoctonia solani* AG3 and AG2-1 to potato**

### **Introduction**

This study compares the pathogenicity of AG3 and AG2-1 isolates taken from classic symptoms of *Rhizoctonia* canker and black scurf on potato plants and tubers and from sclerotia and hyphae from the roots of fodder and mustard *Brassica* in rotation trial plots.

### **Materials and Methods**

Inocula of five isolates of *R. solani* AG3 and five of *R. solani* AG2-1 from various sources (Table 36) were prepared by growing the isolates on sterile French white millet seed according to the method of McDonald and Rovira (1985). Millet inoculum was incorporated into a sand-based potting media in 15-cm diameter black plastic pots (16 propagules/kg). Pots were planted with a single potato minituber derived from tissue-cultured plantlets (cv. Russet Burbank). Control treatments were prepared using sterile millet seeds. The pots were arranged in a randomised complete block design with four replications on glasshouse benches. Glasshouse temperatures were maintained at 15°C night and 25°C day and pots were watered to saturation twice daily.

The experiment was destructively harvested at two times, first when potatoes were at late set and the second when potato plants had senesced ('post-senescence'). Disease and yield variables were assessed and recorded for both harvest times. The incidence of stems affected with *Rhizoctonia* canker, the severity of stem and stolon cankers, the incidence of tubers with sclerotia and the number of sclerotia/tuber were recorded. The incidence of stems with aerial tubers was assessed before plant senescence. The total yield of tubers and number of tubers per plant were also recorded.

An analysis of variance (ANOVA; Genstat for Windows 5<sup>th</sup> Edition ™; Lawes Agricultural Trust, Rothamsted Experimental Station) was used to statistically compare the pathogenicity of isolates for all variables except the proportion of tubers with sclerotia, which was analysed using regression analysis.

### **Results**

All five isolates of AG3, including the one from sclerotia on *Brassica* roots, were pathogenic to potatoes causing characteristic light to dark tan necrotic lesions on potato sprouts and stolons and developing sclerotia on tubers (Table 36 and Table 37). The severity of stem canker ranged from 3.00 to 3.90, on a scale of 5 (average 3.6) with between 80-100% of stems affected (average 92.9%). The severity of stolon canker ranged from 1.00-3.67 on a scale of 0-5 (average 2.3). All isolates produced sclerotia on tubers. Between 85-100% of mature tubers were affected with the black scurf symptom with an average of 15 to 38 sclerotia per tuber (Table 37). Only one AG3 isolate resulted in the development of tubers in the leaf axils (aerial tubers) above ground (Table 37).

All five isolates of AG2-1 damaged potato stems and stolons causing symptoms consistent with those caused by AG3. However, there was a higher level of variation in the incidence of damaged stems (41-95% stems affected) and the severity of stem canker (1.00-3.17) and

stolon canker (1.00-3.50) between AG2-1 isolates than between the AG3 isolates (Table 36). The isolate taken from clover was the least pathogenic to potatoes.

On average, AG3 isolates affected 92.9% of stems with a stem canker severity rating of 3.6 compared with AG2 isolates which affected 72.9% of stems with a severity of 2.2 ( $P \leq 0.001$ ). Two of the AG2 isolates (R4.2 and R1.6) produced very severe cankers on stolons.

Only two of the five AG2-1 isolates (R1.2 and 30411) produced sclerotia on tubers (91% and 96% of tubers affected with 20-24 sclerotia/tuber, respectively) (Table 36 and Table 37). Both isolates were originally isolated from sclerotia on potato tubers. Two AG2-1 isolates (R1.6 and R4.2) damaged tubers, causing lesions covered with hyphae of *R. solani*, affecting 25% or more of the tuber surface. Isolate R4.2 also caused tubers to be misshapen and 'caused pitting' of the tuber surface. Only one isolate resulted in the development of aerial tubers.

The yield of progeny tubers (total weight) and numbers of tubers did not vary significantly between isolates ( $P > 0.05$ ), although potatoes grown with AG2-1 isolate R4.2 produced the smallest tubers overall.

## **Discussion**

This study confirms the results of the previous study (Experiment 1) that isolates of *R. solani* AG2-1 from potato fields in Victoria are pathogenic to potatoes causing cankers on the stems and stolons. However, compared to AG3, the pathogenicity of the AG2-1 isolates was more variable, with some being only mildly pathogenic and others being highly pathogenic to both stems and stolons. This is in contrast to other studies that reported isolates of AG2-1 to be either avirulent or only mildly virulent to potatoes (Carling and Leiner 1986; Chand and Logan 1983). It may be possible that isolates of one group from different locations may vary in their virulence to potatoes and other hosts.

Only two of the five AG2-1 isolates tested developed sclerotia on tubers. Sclerotia were generally small and scattered. This explains why only small numbers of AG2 isolates were found on the surface of tubers affected by classic black scurf in a study of the fungus in potato crops (Section 4.4.1). Notably, the two AG2 isolates that produced sclerotia on tubers in this pathogenicity test were originally isolated from sclerotia on tubers.

More extensive studies are needed to determine the relative abundance of AG2 isolates in potato production systems and their relative importance in the Rhizoctonia disease complex. It is not known whether AG3 and AG2 are competitors or whether they occupy different niches in the potato crop and other crops with respect to space, time and physical conditions such as soil moisture, temperature and biological activity. Furthermore, the pathogenicity study reported here was conducted in a relatively sterile sand-based potting media where potatoes were only challenged by one isolate. It is important to determine whether the pathogenicity of the isolates is different in a more natural soil environment where the fungus must compete with other soil biota.

**Table 36 The effects of *Rhizoctonia solani* AG3 and AG2-1 isolates on the incidence and severity of stem and stolon canker, the incidence and severity of black scurf and the yield and numbers of tubers per plant in a glasshouse experiment – late tuber set**

Isolate	Anastomosis group	Source of isolate	% stems with cankers	Severity of stem canker (0-5) <sup>A</sup>	Severity of stolon cankers (0-5) <sup>A</sup>	Total weight of progeny tubers per plant (g)	No. of progeny tubers per plant	% tubers with sclerotia	No. of sclerotia per tuber
R1.5	AG2-1	Lesions on clover roots	41.4	1.00	1.00	40.18	6.17	0.00	0.00
R1.2	AG2-1	Sclerotia on tubers	62.50	2.17	2.17	52.58	7.17	79.90	3.05
R4.2	AG2-1	Lesions on <i>Brassica</i> roots	94.50	2.17	3.50	34.40	5.00	0.00	0.00 <sup>B,C</sup>
R1.6	AG2-1	Canker on potato stem	76.10	2.67	3.50	27.22	4.50	0.00	0.00 <sup>B</sup>
30411	AG2-1	Sclerotia on tubers	90.00	3.17	1.83	28.98	5.50	40.2	2.37
30392	AG3	Sclerotia on tubers	79.20	3.00	2.17	35.96	6.17	69.80	4.35
D2.1CT	AG3	Canker on potato stem	94.50	3.42	2.17	47.34	6.83	95.20	14.83
30435	AG3	Sclerotia on tubers	100.00	3.83	3.67	36.19	6.00	93.00	7.77
R1.1	AG3	Sclerotia on tubers	91.10	3.83	1.00	36.79	7.00	59.50	3.28
R1.4	AG3	Sclerotia on <i>Brassica</i> roots	100.00	3.92	2.50	37.68	5.67	70.9	3.33
Uninoculated control			0.00	0.00	0.0	45.53	6.50	0.00	0.00
F test P value			<0.001	<0.001	<0.001	0.156	0.688	<0.001	<0.001
Istd (P=0.05)			20.04	0.78	0.66	17.43	2.76	23.90	4.37

<sup>A</sup> Severity rating on scale of 0-5: 0, healthy; 1, <25%; 2, between 25-50%; 3, between 50-75%; 4, >75% of stem or stolon surface with lesions; 5, dead moribund<sup>B</sup> Isolate caused large sunken lesions on the tuber surface<sup>C</sup> Isolate caused tubers to be misshapen

**Table 37 The effects of *Rhizoctonia solani* AG3 and AG2-1 isolates on the incidence of stems with aerial tubers, the yield and number of tubers per plant and on the incidence and severity of black scurf on tubers in a glasshouse experiment - post senescence**

Isolate	Anastomosis group	Source of isolate	No. of stems with aerial tubers	Total weight of progeny tubers per plant (g)	Total number of progeny tubers per plant	Weight per tuber (g)	% tubers with sclerotia	No. of sclerotia per tuber
R1.5	AG2-1	Lesions on clover roots	0.00	97.21	6.67	15.32	0.00	0.00
R1.2	AG2-1	Sclerotia on tubers	0.00	102.55	6.00	23.13	91.20	19.94
R4.2	AG2-1	Lesions on <i>Brassica</i> roots	0.61	71.82	8.17	9.86	0.00	0.00 <sup>A,B</sup>
R1.6	AG2-1	Canker on potato stem	0.00	111.41	5.83	22.52	0.00	0.00 <sup>A</sup>
30411	AG2-1	Sclerotia on tubers	0.00	85.79	5.67	18.90	95.80	23.65
30392	AG3	Sclerotia on tubers	0.00	113.63	8.17	14.72	85.20	20.87
D2.1CT	AG3	Canker on potato stem	0.00	82.49	4.50	20.15	100.00	38.20
30435	AG3	Sclerotia on tubers	0.00	90.40	7.67	13.25	92.70	15.31
R1.1	AG3	Sclerotia on tubers	0.00	86.32	5.00	23.05	100.00	38.4
R1.4	AG3	Sclerotia on <i>Brassica</i> roots	0.17	90.74	7.17	12.62	93.40	18.10
Uninoculated control			0.00	110.58	6.83	17.27	0.00	0.00
F test P value			0.002	0.257	0.615	0.311	<0.001	<0.001
Istd (P=0.05)			0.31	33.58	3.87	11.84	11.71	16.59

<sup>A</sup> Isolate caused large sunken lesions on the tuber surface<sup>B</sup> Isolate caused tubers to be misshapen

#### 4.4.3 A new disease of potatoes attributed to *Rhizoctonia solani*

##### The disease

In February and March 2001, several mature potato crops at different locations north and north west of Ballarat (Newlyn, Ascot and Waubra) were affected by a serious wilt during a prolonged period of very hot weather (up to several days of soil temperatures exceeding 20°C). The affected crops were of different ages, having been planted up to a month apart, but all had closed canopies. Symptoms of disease in the tops of plants included yellowing, a 'cupping' of the leaflets (leaflets curled upwards towards the main vein), wilting and complete collapse and death of the plant. Individual plants in a row were affected or several plants in patches which were up to several meters across. A white/grey mycelium of several centimetres diameter was visible on the soil surface around the base of affected plants. The subterranean parts of the stems of affected plants had a characteristic girdling necrosis, similar to the 'wirestem' symptom just below the soil line. This symptom could be confused with that caused by *Sclerotinia* spp (Powelson 2001) or high temperature injury (Thornton 2001). Cankers on tubers were also common. Hyphae, characteristic of *R. solani*, grew rapidly over affected subterranean plant parts after 12 hours moist incubation. Similar symptoms had been observed in crops in the Central Highlands region during the previous two seasons. Fatten seedlings (*Chenopodium album* L.) and seedling clovers (type unknown) growing in affected patches also had symptoms of wilting. Stems below ground displayed characteristic 'wirestem' symptoms.

Symptoms of wilting became apparent in all crops around the same time in February, even though the crops were all at different stages of growth (planted as much as a month apart). The only common feature between the affected crops was that they were planted after a pasture phase of two or more years duration.

Microscopic examination of the fungus growing on the plant stems, tubers and on the soil revealed a *Rhizoctonia solani* like fungus. This study reports on the isolation, identification, characterisation and pathogenicity of this fungus.

##### Sampling, isolation and characterisation of *Rhizoctonia solani*

Potato plants, fatten, clover and organic debris (grass crowns) were sampled from diseased crops in February and March 2001. Isolations were done as described in Section 4.4.1. A fungus with characteristics consistent with those of *Rhizoctonia solani* was isolated with high frequency from potato stems and sclerotia taken from crops affected by the wilt. *R. solani* was also isolated from 'wirestem' symptoms on the stems of fatten and clover seedlings and from organic debris (grass crowns) found in the patches of wilted potato plants.

Anastomosis grouping of *R. solani* isolates collected from diseased crops was done as described in Section 4.4.1 against the tester isolates of AG1, AG2-1, AG2-2, AGs 3-6 and AG's 8-11 (Table 32).

Most of 43 isolates (81%) taken from stems and tubers affected by the undescribed wilt attributed to *R. solani* belonged to AG2 (16 AG2-1, 19 AG2-2) (Table 38). *R. solani* AG2-2 was isolated from the diseased stems of fatten in Rhizoctonia patches in crops affected by wilt. Both AG2-1 and 2-2 were isolated from the diseased roots of clover seedlings in the same patches, as well as from organic debris taken from the same patches.

**Table 38** Anastomosis grouping of isolates of *Rhizoctonia solani* collected from subterranean parts of potato plants, other plant species and organic debris from crops affected with a wilt disease in the Central Highlands of Victoria during February/March 2001

Source	No. tested	AG3	AG2-1	AG2-2	AG4	AG5	Others (no reactions with testers)
Lesions on stems	14	1	5	8	0	0	0
Sclerotia on stems	12	0	4	6	0	0	2
Sclerotia on tubers	15	2	7	5	0	0	1
Lesions on fatten hypocotyls	2	0	0	2	0	0	0
Lesions on clover crowns	5	0	2	2	0	0	1
Organic debris	6	0	3	0	0	0	3
<b>Total</b>	<b>54</b>	<b>3</b>	<b>21</b>	<b>23</b>	<b>0</b>	<b>0</b>	<b>7</b>

These results show that isolates of *R. solani* isolated from plants affected by a severe wilt almost exclusively belonged to AG2-1 and AG2-2. This disease has not previously been described and it is proposed that it be called Rhizoctonia wilt to distinguish it from better known Rhizoctonia canker and black scurf.

#### *A comparison of the pathogenicity of isolates of Rhizoctonia solani AG2-1 and AG2-2 from a new disease complex to potatoes in a glasshouse experiment*

#### Introduction

*Rhizoctonia solani* AG2-1 and AG2-2 were the predominant groups isolated from potato parts, fatten, clover and grass crowns in crops affected by Rhizoctonia wilt. A previous study showed that some isolates of AG2-1 from potatoes with classic Rhizotonia canker or black scurf and from the roots of *Brassica* spp. were highly pathogenic to potatoes (Pathogenicity Experiments 1 and 2, Section 4.4.2). A selection of isolates were tested for their pathogenicity to potatoes in a glasshouse experiment in order to satisfy Koch's postulates.

#### Material and Methods

Inocula of four isolates of *R. solani* AG2-1 and six of *R. solani* AG2-2 from were prepared by growing the isolates on sterile French white millet seed according to the method of McDonald and Rovira (1985). Millet inoculum was incorporated into a sand-based potting media in 15-cm diameter black plastic pots (16 propagules/kg). Pots were planted with potato minitubers derived from tissue-cultured plantlets (cv. Riverina Russet). Control treatments were prepared using sterile millet seeds. The pots were arranged in a randomised complete block design with six replications on glasshouse benches. Temperature in the glasshouse was set for day /night at 23°C/17°C in an attempt to simulate prolonged periods of hot weather when the disease appeared in the field.

The experiment was destructively harvested at two times, first when potatoes were at late tuber set and the second when potato plants had senesced ('post senescence'). Disease and yield variables were assessed and recorded at both harvest times. The incidence of stems

affected with *Rhizoctonia* canker, the severity of stem and stolon cankers, the incidence of tubers with sclerotia and the number of sclerotia/tuber were recorded. The incidence of stems with aerial tubers was assessed before plant senescence. The total yield of tubers and number of tubers per plant were also recorded.

An analysis of variance (ANOVA; Genstat for Windows 5<sup>th</sup> Edition <sup>TM</sup>; Lawes Agricultural Trust, Rothamsted Experimental Station) was used to statistically compare the pathogenicity of isolates for all variables.

## Results

All isolates damaged potato plants. All but one isolate (AG2-1 30255) caused stem cankers, even though all isolates caused stolon cankers (Table 39). The severity of symptoms caused by the different isolates varied considerably and ranged from slight to severe. One isolate of AG2-2 caused particularly severe stem and stolon cankers (ratings of 3.33 and 4.17, respectively). Generally, the severity of stem canker appeared to be correlated with the severity of stolon canker.

All isolates produced sclerotia on tubers with incidence ranging from 9-38% of tubers affected, although sclerotia were generally small and relatively uncommon on each tuber (Table 39). Three isolates (AG2-1, 30293; AG2-2, 30259 and 30286) formed sclerotia on plant stems and one (30260) formed sclerotia on roots. All isolates produced dark brown necrotic lesions or cankers on potato tubers that in some cases affected more than 50% of the tuber surface. Four isolates (AG2-1, 30255, 30293, 30260; AG2-2, 30259) caused misshapen tubers.

Potato plants affected by five isolates (AG 2-1, 30293, 30260; AG2-2, 30295, 30276, 30286) showed a high degree of wilting of foliage when plants matured. One isolate (AG2-2, 30276) caused a significant ( $P<0.05$ ) reduction in the average size of tubers compare with uninoculated controls and two isolates (AG2-1, 30293; AG2-2, N-06hpst) tended to reduce the total yield of tubers per plant ( $P<0.1$ ).

## Discussion

All isolates of AG2-1 and AG2-2 tested here were pathogenic to potatoes producing cankers on stems, stolons or on both organs. They also produced cankers and sclerotia on tubers and misshapen tubers. However, the isolates varied considerably in their pathogenicity, ranging from mildly to highly virulent on stems, stolons and tubers. Sclerotia tended to be small and scattered. These symptoms were consistent with those reported in previous pathogenicity tests with AG2 isolates (Section 4.4.2, Experiments 1 and 2). There did not appear to be any discernible differences in pathogenicity between AG2-1 and AG2-2 isolates. A known high level of genetic variation between isolates of AG2 (Liu and Sinclair 1992) may explain the high variation in virulence of the isolates tested here.

All isolates tested here were taken from plants affected by a necrotic girdling of the main stems of mature plants just below the soil surface. This symptom was not reproduced in the glasshouse pathogenicity test, although plants affected by a number of the AG2-1 and AG2-2 isolates showed signs of wilting. The symptoms of stem damage seen on plant stems in the field were similar to those described for high temperature injury by Thornton (2001) or damage by *Sclerotinia* species. One of the main factors linking the wilt disease

at the different locations was several days of hot, dry weather. Soil temperatures were estimated to be around 20°C over that period. The crop canopies were closed and heavy irrigation during the hot conditions would have resulted in very warm, moist soil and a humid environment under the canopy. It may be possible that high temperatures caused some stem damage at the soil/air interface, predisposing the plants to infection by the AG2 strains of *R. solani*. The field conditions associated with the wilt disease are difficult to duplicate in the glasshouse and further tests need to be done in controlled environment cabinets.

There is evidence of 'cold' and 'warmth' preferring isolates of *R. solani* (Dijst and Schneider 1996; Doornik 1980; Doornik 1981). It is possible that isolates of AG2-1 and AG2-2 isolated from wilted plants are more pathogenic at higher temperatures. Classic symptoms of canker on young stems and stolons incited by *R. solani* AG3 tend to occur under relatively dry, cool (7-13°C) conditions (Carling and Leiner 1990; Hilton and Kyritsis 2001) early in the season during the period of sprout emergence and tuber formation. It may be that AG3 has a competitive advantage over AG2 isolates at 'cool' temperatures and that AG2 isolates have a competitive advantage over AG3 isolates at 'warm' temperatures. Further characterisation of AG3 and AG2 isolates with regards to growth rates and virulence under different temperatures needs to be done.

*Rhizoctonia solani* AG2-1 and AG2-2 have not been reported as being major pathogens of potatoes before. Rather, others report mild virulence or no virulence on potatoes when testing the pathogenicity of AG2 isolates on potatoes (Chand and Logan 1983). The AG2's have been associated with fodder legumes, such as clovers, and oilseed and fodder brassicas (Hwong *et al.* 1996; Khangura *et al.* 1999; Wong and Sivasithamparam 1985). Frequent potato cropping supports *R. solani* AG3 (Jager and Velvis 1995). It is also likely that the pasture-potato cropping systems studied in Victoria, where pastures include fodder legumes and fodder *Brassica* are commonly grown in rotation with potatoes, support relatively high populations of AG2s. Further studies are required to determine the ecology of AG2s in these cropping systems, and the relative importance of this crop in the *Rhizoctonia* disease complex of potatoes.

**Table 39 The effects of isolates of *Rhizoctonia solani* AG2-1 and AG2-2 on stem and stolon canker, black scurf, tuber number and yield in potatoes at two different growth stages in a glasshouse experiment**

Isolate	Anastomosis group	Post emergence – pre-flowering assessment		Post-senescence assessment					
		Stem canker		Stolon canker		Total No. of tubers	Average weight/tuber (g)	Total tuber weight/plant (g)	% tubers with sclerotia
		No. of stems affected (out of total)	Severity (0-5) <sup>A</sup>	Severity (0-5) <sup>A</sup>					
30255	AG 2-1	0 (16)	0.00	1.50	6.00	26.6	113.3	15.3	1.13
30284	AG 2-1	3 (11)	0.33	0.10	3.83	22.0	81.8	37.5	1.79
30260 <sup>B</sup>	AG 2-1	5 (16)	1.17	2.67	5.33	28.0	124.8	29.0	0.55
30293 <sup>B</sup>	AG 2-1	10 (12)	2.67	2.00	7.17	10.1	61.9	9.4	0.37
30295 <sup>B</sup>	AG 2-2	3 (11)	0.83	1.17	5.67	18.2	85.7	26.3	1.06
30286 <sup>B</sup>	AG 2-2	2 (12)	0.83	0.83	6.00	13.5	103.2	15.0	0.55
30259	AG 2-2	7 (12)	1.00	1.50	5.83	15.2	88.6	38.0	0.58
N-06hpst	AG 2-2	6 (11)	1.60	1.85	5.17	13.3	72.2	15.5	1.01
30283	AG 2-2	7 (14)	1.83	1.67	5.67	18.2	99.3	13.0	0.19
30276 <sup>B</sup>	AG 2-2	14 (17)	3.33	4.17	8.50	4.3	42.2	24.5	1.54
Uninoculated control		1 (10)	0.20	0.10	6.67	20.4	132.8	0.00	0.00
F-test P value			0.002	<0.001	0.755	0.032	0.081	0.200	0.465
Istd (P=0.05)			1.58	1.71	4.16	13.37	56.87	28.20	1.59

<sup>A</sup> Severity rating on scale of 0-5: 0, healthy; 1, <25%; 2, between 25-50%; 3, between 50-75%; 4, >75% of stem or stolon surface with lesions; 5, dead moribund

<sup>B</sup> Potato plants had symptoms of wilting

#### 4.4.4 General Discussion

This study confirmed *R. solani* AG3 as the most common group associated with Rhizoctonia canker and black scurf on potatoes in two different potato cropping areas of Victoria accounting for two thirds of all isolates collected from stem cankers and progeny tubers. However, *R. solani* AG2-1 and AG2-2 were also commonly isolated from Rhizoctonia stem cankers accounting for about 25% of all isolates collected. AG2-1 and AG2-2 were also associated with a wilting disease that affected mature potato crops during prolonged periods of unusually hot weather. Pathogenicity tests showed that the AG2s were pathogenic to potatoes causing stem and stolon cankers, cankers on tubers and misshapen tubers. This contradicts other studies that report the AG2s to be non-pathogenic or only mildly pathogenic to potatoes (Carling and Leiner 1986; Chand and Logan 1983). This is the first report of isolates of AG2-1 and AG2-2 being highly pathogenic to potatoes.

The AG2 isolates proved to be pathogenic to *Brassica* species (fodder rape and Indian mustard) and red clover in glasshouse tests. Wong and Sivasithamparam (1985) reported isolates of *R. solani* AG2-1 and AG2-2 to be highly virulent on clover (Leguminosae), causing seedling blight, damping-off and root rot. The AG2-1s are also known as pathogens of the Cruciferae, including *Brassica* spp. such as oilseed rape, whereas the AG2-2s are often associated with Chenopodiaceae, mainly sugar beet, or some Graminae (Ogoshi A 1987). The prevalence of clover in pastures and the use of fodder rape in rotation with potatoes may account for the relatively high incidence of this group in Victoria.

This study showed that *R. solani* AG3, the potato 'strain' was able to grow epiphytically on the roots of fodder rape, forming survival structures, the sclerotia, without causing damage. Others have also reported that *R. solani* AG3 can grow epiphytically on the roots of several different plant genera (Carling *et al.* 1986). The fungus was isolated from below ground parts of barley, winter wheat, ryegrass, clover and other crops in potato production areas in Canada (Celetti *et al.* 1989b; Celetti *et al.* 1989a). In pathogenicity tests reported here, AG3 isolates were only mildly pathogenic to fodder rape, Indian mustard and red clover. This means the a fodder rape crop may not be a good 'break' crop for the management of Rhizoctonia diseases in potatoes and may, in fact, maintain populations of AG3 after potatoes.

Along with AG3 and AG2, a small proportion of AG4 and AG5 were also found in potato crops in Victoria. Balali *et al.* (1995) also reported finding a number of AG4 and AG5 in potato crops in a study in South Australia. AG4s are usually associated with the Chenopodiaceae, the Leguminosae and the Solanaceae and those of AG5 with the Leguminosae, Solanaceae and soil (Ogoshi A 1987). AG4 is particularly aggressive in damaging potato roots but can also cause severe stem and stolon canker (Balali *et al.* 1995). This group does not form black scurf on tubers, even though it can produce sclerotia (Balali *et al.* 1995). AG5 can damage roots, stems and stolons and also causes black scurf, but is generally considered to be less aggressive than AG3 (Banville *et al.* 1996). AG4 is considered to prefer warmer temperatures (Banville *et al.* 1996), although Balali *et al.* (1995) reported that AG5 isolates were only found in the warmer potato cropping areas of South Australia.

#### Implications for crop rotation

The relative distribution and abundance of the different AG3 groups in a particular cropping system can be affected by cropping history, climate and competition. The presence of AG2s

in potatoes in Victoria may be due to the prevalence of fodder legumes and fodder rape. In a study in Canada, Gudmestad *et al.* (1989) found that anastomosis groups 4 and 5 were the predominant groups recovered from potato plants sampled in fields not previously cropped to potatoes, while AG3 and AG5 were most frequently recovered from fields with a history of potato production.

The different AGs may occupy different niches in a potato crop perhaps depending on their preference for particular temperatures or their ability to compete with each other. In a study in Mexico, Virgen-Calleros *et al.* (2000) isolated AG3 from the potato crop throughout the season, whereas AG4 was only found during the flowering stage. Anguiz and Martin (1989) reported that AG4 was more common under warm moist conditions found at sea level, compared with AG3 which was present at higher altitudes where cooler conditions prevail. Balali *et al.* (1995) suggested that in South Australia, AG4 and AG5 may be more common in warmer cropping areas because of their preference for 'warmth' and where they might have an advantage over AG3 which appears to favour cooler conditions (Anguiz and Martin 1989; Carling and Leiner 1990). Some isolates of AG2 are also said to be 'warmth' preferring isolates (Dijst and Schneider 1996). Competition between the different groups may be important and Jager and Velvis (1995) reported that *in vitro*, AG5 was an inferior competitor to AG3. The ability of AG3 to produce relatively large and abundant sclerotia, compared with AG2 and AG5 for instance, will mean that it always has a competitive advantage in a potato cropping environment because it can readily be reintroduced into a potato crop on seed tubers.

All these factors indicate that much more is to be learnt about *R. solani* under Australian conditions. What is the relative importance of AG2 in the potato crop and does AG2 compete well with AG3 or does it have a different niche? Does AG2 prefer warmer conditions to AG3? How do the different crops grown in rotation with potatoes affect the relative abundance of AG2 and AG3?

#### **4.5 The influence of methods of seed-bed preparation on potato disease and yield in a pasture-potato system**

### **Background**

One aspect of crop rotation that is often underestimated is the method of preparing a seedbed before sowing a crop in the rotation cycle. This could also influence pathogens and the growth and yield of that crop. Various components of seedbed preparation include:

- timing of seedbed preparation, ie, the timing of the first cultivation or application of herbicide, which may range from just before to several weeks or more before sowing resulting in 'fallow' periods of varying duration.
  - the use of herbicides, a combination of herbicides and soil cultivation or soil cultivation alone to kill the existing crop, pasture or weeds;
  - different methods of cultivating the soil (mouldboard ploughing, sub-surface cultivation, harrows etc.)

These factors can affect soil structure, chemistry, microbiology, drainage, as well as insect, pathogen and weed populations, which in turn can affect plant emergence, growth, disease and yield. The effects of the method and timing of the seed-bed preparation prior to sowing potatoes after pasture on disease and yield and the effects of spraying-off pasture species with herbicides on the survival of *Rhizoctonia solani* on roots are described in this report.

#### 4.5.1 The effect of method and timing of seed-bed preparation on Rhizoctonia stem canker, black scurf and other diseases, and on the yield of potatoes

## Summary

The effect of fallowing on disease and yield of potatoes was examined in a field trial near Ballarat, Victoria. Long-term pasture was ploughed-in 80 days before or 46 days before planting potatoes ('early' or 'late' cultivation), resulting in a 'long' or short' fallow, or sprayed-off with glyphosate 85 days and cultivated 46 days before planting potatoes (long chemical fallow). The different methods of seed-bed preparation did not significantly affect the incidence and severity of *Rhizoctonia* stem canker in the young crop, nor the incidence and severity of silver scurf, black dot and powdery scab on progeny tubers. The incidence and severity of black scurf was 30% less in the late compared with the early cultivated treatment, perhaps because of potentially higher biological activity associated with organic debris in the soil cultivated later. A better understanding of how the different plant species grown in rotation with potato affect activity and survival of *R. solani* will help in developing seed-bed preparation strategies that minimise pathogen populations.

## Introduction

In many areas of Australia, potatoes are traditionally sown after a pasture phase. *Rhizoctonia solani* can be transmitted to a new crop by planting seed potatoes with black scurf (sclerotia). However, there is evidence that the fungus is soil-borne in traditional cropping areas and also in paddocks cropped to potatoes for the first time (RF de Boer, unpublished data) (Cother 1979). In a survey around the Ballarat area during 1996/97, a high incidence of stem canker was apparent in crops sown after five or more years of pasture (Section 4.1).

There is anecdotal evidence that the risk of stem canker can be reduced by early cultivation of a pasture and the development of a 'fluffy' seed-bed ('fine tilth'). In the absence of a host, *R. solani* is considered to survive in soil in the form of thick-walled mycelia or sclerotia associated with organic debris (Boosalis and Scharen 1959; 1996; Papavizas 1968). It can be hypothesised that a fallow period after pasture may reduce inoculum of *R. solani* and disease in subsequent potato crops. Research with cereal crops showed that the incidence and severity of root rot of wheat caused by *R. solani* AG 8 was significantly reduced when wheat was direct-drilled after a fallow period (de Boer 1994; Roget *et al.* 1987).

A field trial was conducted to compare the effects of conventional seed-bed preparation in early September with a later ploughing-in of pasture, involving a four week longer fallow, on stem canker and black scurf and on yield and quality in a potato crop planted in the spring.

## Materials and Methods

A field experiment was established on a ferrosol (1996) soil in a traditional potato production area near Ballarat, in Victoria, during the winter of 1997. Paddock history was a potato crop followed by fodder rape and three years of a perennial ryegrass/clover pasture in a 1 in 4 rotation. This site has a history of severe *Rhizoctonia* disease in potato crops. Experimental treatments included three cultivation/fallow treatments with two urea treatments (nil or 150 kg/ha) arranged as a randomised complete block of 6 treatments replicated 6 times. Cultivation treatments included 'Early' cultivation (Conventional; 2 September), 'Late' cultivation (6 October, 46 days before potatoes) or a Roundup® herbicide application (2L/ha, 28 August) followed by late cultivation ('Herbicide + Late'; 6 October). The 'Early' and 'Late' treatments were essentially 'long' and 'short' cultivated fallows and the 'Herbicide + Late', a 'long' chemical fallow, respectively, starting 80, 46 or 85 days before planting potatoes. Initial cultivation was with a mouldboard plough. Follow-up cultivation close to sowing time involved consecutive workings of all treatments with a chisel plough (sub-surface cultivation), a scarifier and a power harrow. Urea was applied as a soil spray before ploughing to facilitate decomposition of organic residues. Plots were 6 rows wide by 14.3 m long.

Untreated seed potatoes (cv. Russet Burbank) were planted with a commercial cup planter on the 22 November. Black scurf was not detected by visual inspection in a sample of 35 washed seed tubers. Crop management was as for a commercial Russet Burbank crop. Various parameters of plant establishment, growth, and disease were assessed throughout the trial. Results were analysed by Analysis of Variance of a 3 by 2 factorial design (ANOVA; Genstat for Windows 5<sup>th</sup> Edition™; Lawes Agricultural Trust, Rothamsted Experimental Station).

## Results

Generally, the application of urea had no significant effect on plant emergence, yield or disease. There were no significant interactions ( $P>0.05$ ) between cultivation and urea treatments for these parameters and, therefore, only the main effects of cultivation treatments are reported here.

The influence of treatments on crop emergence, growth and disease are presented in Table 40. Plant emergence, which averaged 89%, was reduced by *Rhizoctonia* stem canker and affected by uneven planting, but did not vary significantly ( $P>0.05$ ) with cultivation treatments. On average, 53% of plants showed some degree of stunting (plant size reduced by

25% or more) during early crop growth. The severity of stunting (scale 0-3) was 7 to 15% less ( $P \leq 0.05$ ) in the Late cultivated compared with the Early cultivated and Herbicide treatments, respectively. Overall, significantly more ( $P \leq 0.05$ ) plants had some degree of stunting in Urea compared with the no Urea treatments (Table 40).

The results of the effects of treatments on diseases incidence and severity are presented in Table 40. The incidence and severity of stem canker, and the incidence of late senescent plants with aerial tubers were not affected significantly ( $P > 0.05$ ) by cultivation treatments. The incidence and severity of black scurf on tubers at harvest were approximately 30% less ( $P \leq 0.05$ ) in the Late cultivated than in the Early cultivated treatment, but did not differ significantly ( $P > 0.05$ ) from the Herbicide treatment. The incidence and severity of black dot (*Colletotrichum coccodes*), silver scurf (*Helminthosporium solani*) and powdery scab (*Spongospora subterranea*), were not affected significantly ( $P > 0.05$ ) by cultivation treatments (average of 85%, 22% and 50% of tubers affected, respectively).

Total and marketable yield were not affected significantly ( $P > 0.05$ ) by cultivation treatment (Table 41). The number and yield of tubers in the different size categories (<75 g, 75-280 g, 280-350 g, 350-450 g, >450 g) did not differ significantly ( $P \leq 0.05$ ) with treatment, except for the 75-280 g category in which there were fewer tubers and lower yields ( $P \leq 0.07$  & 0.05, respectively) in the Herbicide compared with the Late cultivated treatment.

## Discussion

In this study, there were no major differences in the incidence and severity of damage caused by *R. solani*, nor on the yield and quality of potatoes between long and short cultivated fallows and the long chemical fallows. Similarly, the incidence and severity of silver scurf, black dot and powdery scab on progeny tubers were not affected by the different treatments.

The lower incidence and severity of black scurf in the Late compared with the Early cultivation treatment may possibly have been related to potentially higher levels of soil biological activity and potential competition in that treatment. The Late treatment had a longer period of pasture growth, and therefore more debris at the time of planting potatoes. It can be hypothesised that the retention of crop residue results in more microbial activity and competition among saprophytic organisms resulting in suppression of the activity of the pathogen (Gudmestad *et al.* 1978; Sturz *et al.* 1997). However, it is not known why the incidence of tubers was affected but not the incidence of Rhizoctonia damage to the stems.

Research on Rhizoctonia damage in cereal crops clearly shows that fallowing and soil disturbance reduces the inoculum of *R. solani* AG8. Perhaps longer periods of fallow are needed in potato production to reduce inoculum. Unlike AG8, which survives as hyphae in organic debris, AG2 and AG3 also form sclerotia. The decline of the food base through fallowing (cultivated or chemical) could stimulate the production of sclerotia and increase the inoculum in soil. Much needs to be learnt about the relationship between *R. solani* and pasture in terms of the activity of the fungus and its survival. If, for example, the fungus survives best in the clover fraction of the pasture, it may be necessary to remove this component some time before sowing potatoes. Studies are also needed to determine whether chemically spraying-off pasture with herbicides has an effect on the population of the pathogen compared with conventional cultivation.

**Table 40 The effects of method and timing of seed-bed preparation on plant emergence, the incidence and severity of stunted plants and stem canker during early crop growth, the incidence of plant with aerial tubers at late senescence and on the incidence of black scurf, black dot, silver scurf and powdery scab on the progeny tubers at harvest, Clarks Hill 1997/98.**

Treatments	Emer-gence	Post emergence - flowering				Mal-formed plants <sup>E</sup>	Tuber diseases							
		% plants	Stunting Inc <sup>A</sup>	Sey <sup>B</sup>	Stem canker Inc <sup>A</sup>	Sev <sup>C</sup>	Inc <sup>A</sup>	Black scurf Inc <sup>A</sup>	Sev <sup>D</sup>	Black dot Inc <sup>A</sup>	Sev <sup>D</sup>	Silver scurf Inc <sup>A</sup>	Sev <sup>D</sup>	Powdery scab Inc
<b>Cultivation/Urea (U)</b>														
Early	89.0	49.3	0.82	46.1	1.18	12.7	51.0	0.84	82.8	1.51	22.3	0.28	42.0	0.51
Early + U	89.5	55.5	0.90	41.7	1.08	16.4	60.5	1.04	81.3	1.47	21.5	0.27	47.2	0.67
Late	90.2	50.2	0.78	54.1	1.12	19.8	35.8	0.66	82.3	1.47	27.3	0.39	53.7	0.70
Late +U	90.2	52.8	0.81	41.1	0.91	13.7	38.5	0.62	87.5	1.45	18.3	0.22	57.5	0.73
Herbicide +	88.7	51.8	0.87	48.5	1.17	18.4	52.0	0.84	84.5	1.66	19.8	0.28	50.2	0.69
Late														
Herbicide +	88.5	59.3	1.01	51.2	1.17	17.8	42.7	0.67	89.0	1.80	25.2	0.36	51.7	0.74
Late + U														
<b>Cultivation effects</b>														
Early	89.25	52.4	0.86	43.9	1.13	14.6	55.7	0.94	82.1	1.48	21.9	0.29	44.6	0.60
Late	90.17	51.5	0.80	47.6	1.01	16.7	37.2	0.64	84.9	1.46	22.8	0.30	55.6	0.72
Herbicide +	88.58	55.6	0.94	49.8	1.17	18.1	47.3	0.76	86.7	1.73	22.5	0.32	50.9	0.71
Late														
F-test P value	0.41	0.40	0.033	0.79	0.80	0.40	0.018	0.025	0.54	0.32	0.99	0.88	0.40	0.49
I.s.d (P=0.05)	2.4	6.69	0.11	17.89	0.51	5.36	12.45	0.21	8.55	0.39	12.03	0.17	16.52	0.25
<b>Urea effects</b>														
No Urea	89.28	50.5	0.82	49.6	1.15	17.0	46.3	0.78	83.2	1.54	23.2	0.32	48.6	0.64
+ Urea	89.39	55.9	0.91	44.6	1.05	15.9	47.2	0.78	85.9	1.58	21.7	0.28	52.1	0.71
F - test	0.91	0.05	0.05	0.49	0.60	0.64	0.85	0.99	0.43	0.84	0.76	0.60	0.60	0.46
I.s.d. (P=0.05)	1.96	5.46	0.09	14.61	0.42	4.38	10.17	0.17	6.98	0.32	9.83	0.14	13.49	0.20

<sup>A</sup> Incidence: % plants or tubers affected

<sup>B</sup> Severity rating scale 0-3: 0 = growth unaffected, 3 = severely stunted or not emerged

<sup>C</sup> Severity rating scale 0-5: 0 = no stem canker, 5 = all stems with girdling lesions

<sup>D</sup> Severity rating scale 0-4: 0 = no disease, 4 = >25% of tuber surface covered with sclerotia

<sup>E</sup> Assessed after crop has senesced – malformed plants remain green and have aerial tubers

**Table 41 The effects of method and timing of seed-bed preparation on total and marketable yield, on the yield of misshapen tubers, and on the number and yield of tubers in different size categories, Clarkes Hill 1997/98.**

Treatments	Total Yield (t/ha)	Marketable Yield (t/ha)	Yield of misshapen tubers (t/ha)	Total number and yield of tubers in different size categories							
				<75 g		75-280 g		280-450 g		>450 g	
				No. tubers/plot	Yield (t/ha)	No. tubers/plot	Yield (t/ha)	No. tubers/plot	Yield (t/ha)	No. tubers/plot	Yield (t/ha)
<b>Cultivation/Urea (U)</b>											
Early	53.5	42.9	4.4	136.2	2.99	403.3	33.4	70.3	12.1	16.7	5.0
Early + U	51.2	39.6	6.1	159.5	3.36	407.7	31.5	70.3	12.0	16.8	4.8
Late	50.3	36.6	6.9	143.7	3.17	360.0	28.2	71.3	12.8	20.8	6.2
Late +U	52.8	42.1	3.8	138.8	3.11	400.8	31.9	72.0	12.2	18.7	5.6
Herbicide +	52.5	39.6	6.8	153.5	2.97	377.8	30.6	75.5	13.1	20.8	5.9
Late											
Herbicide +	52.2	40.0	5.7	136.0	2.95	358.7	29.2	77.8	14.0	20.3	6.0
Late + U											
<b>Cultivation effects</b>											
Early	52.56	41.24	5.21	147.8	3.17	405.5	32.84	70.3	12.04	16.8	4.87
Late	51.59	39.36	5.38	141.3	3.14	380.4	30.05	71.7	12.5	19.8	5.89
Herbicide +	52.35	39.81	6.18	144.5	2.96	368.3	29.9	76.7	13.55	20.6	5.94
Late											
F - test	0.70	0.60	2.71	0.90	0.80	0.07	0.05	0.40	0.15	0.40	0.50
I.s.d. (P=0.05)	2.4	4.3	0.73	33.10	0.7	31.7	2.3	10.51	1.6	6.22	1.99
<b>Urea effects</b>											
No Urea	52.23	40.57	5.20	144.8	3.14	389.1	30.9	73.4	12.74	18.6	5.45
+ Urea	52.10	39.71	5.98	144.4	3.01	380.4	30.72	72.4	12.65	19.4	5.68
F - test	0.89	0.62	0.48	0.98	0.73	0.50	0.84	0.81	0.89	0.74	0.77
I.s.d. (P=0.05)	1.94	3.5	2.21	27.03	0.58	25.88	1.87	8.58	1.29	5.08	1.63

#### 4.5.2 The effects of spraying-off perennial ryegrass and white clover plants with the herbicide glyphosate on the survival forms of *Rhizoctonia solani* AG3 and AG2 on roots in a glasshouse experiment

##### Summary

The effects of chemically fallowing pasture on *Rhizoctonia solani* was investigated in a glasshouse pot experiment. Survival forms of *R. solani* AG3 and AG2-1 (melanised hyphal fragments, monilioid cells and sclerotia) were found in perennial ryegrass and white clover in artificially inoculated pots, irrespective of herbicide treatment. The glyphosate treatment resulted in significantly greater numbers of survival forms of *R. solani* AG3 in clover and *R. solani* AG2-1 in grass but had no apparent effect on the AG3 isolate in grass, or on the AG2-1 isolate in clover. This demonstrates that the chemical fallowing of pasture species could potentially increase soil inoculum of both strains of *R. solani* and this has implications for the methods of seed-bed preparation.

##### Introduction

*Rhizoctonia solani* is a collective species (Anderson 1982) which, in the absence of a host, survives in soil in the form of thick-walled mycelia or sclerotia associated with organic debris (Boosalis and Scharen 1959; 1996; Papavizas 1968). Although *R. solani* is a pathogen of a wide variety of plant species, it is also capable of establishing non-symptomatic relationships with many species (Carling *et al.* 1986) as was evident in rotation trials in Victoria (Section 4.4).

In Australia, both seed and soil-borne inoculum of *R. solani* contribute to the *Rhizoctonia* disease complex in a potato crop (RF de Boer and JE Petkowski, unpublished data). Sclerotia of *R. solani* are known to be an important source of inoculum for *R. solani* AG3 in potatoes (Jager *et al.* 1982; Carling and Leiner 1986). As well as developing on the skin of potato tubers, sclerotia develop on other substrates such as the surface of roots of crops grown in rotation with potatoes, including fodder *Brassica* species (Section 4.4) and red clover (Petkowski and de Boer 2001). The fungus colonises the surface of the developing tuber in the potato crop and produces sclerotia as the tuber matures. Removing the potato haulm prematurely, before tubers have fully matured, can stimulate the production of sclerotia on the tuber surface (Dijst 1985). In fact, cutting off the plant top or chemically killing the haulm stimulates sclerotial production to a greater extent than pulling the haulm from the soil. The initiation of sclerotia is governed by chemical exudates leaching from the tuber skin (Dijst 1989).

A study of *R. solani* in rotation trials (Section 4.4) revealed that root systems of pasture species are acting as a substrate for *R. solani*. Preparing the seed-bed for the planting of a potato crop after a pasture phase often involves chemically killing the pasture with 'knockdown' herbicides before the soil is cultivated. A glasshouse study was conducted to test the hypothesis that chemically 'fallowing' a pasture may stimulate the formation of survival forms of *R. solani* in the same way as killing the tops of potato plants does. The effects of killing perennial ryegrass and white clover plants on the development of survival forms (thick walled hyphae, monilioid cells and sclerotia) of *R. solani* AG3 and AG2-1 are reported here.

## Materials and Methods

Inocula of an isolate of *R. solani* AG 3 and one of *R. solani* AG 2-1 were prepared using sterile white millet seed (*Panicum miliaceum* L.) according to the method of McDonald and Rovira (1985). The AG3 isolate was originally taken from a single sclerotium on a potato tuber and the AG2-1 isolate from potato stem canker. The inoculum was incorporated into a river sand mix (fine and coarse particles at 1:2 v/v) at a rate of 16 propagules/kg of sand. Plastic pots containing 0.5 kg of sand mix were sown with perennial ryegrass (*Lolium perenne* L. cv. Cordua) or white clover (*Trifolium repens* L. cv. Sustain) at rates of 6-8 seeds per pot. Uninoculated control treatments for both species were prepared using sterile millet seed. The fertiliser Nitrophoska® was applied at the rate of 2 g per pot at the time of sowing. Liquid fertiliser Aquasol® was applied to all pots four weeks after sowing and, thereafter, every three weeks until the completion of the experiment. Experimental treatments included two pasture species grown with either *R. solani* AG3 or *R. solani* AG2-1, and two herbicide treatments (+ or - glyphosate) applied to each isolate/pasture species combination. Pots were arranged on glasshouse benches in a randomised complete block design with 4 replications. The glasshouse was maintained at 15-25°C and pots were automatically watered to saturation twice per day.

The herbicide Roundup® (7.2g/L glyphosate) was sprayed onto the foliage of the pasture species eight weeks after sowing when grass seedlings were at the tillering growth stage and clover seedlings at the stage of stolon formation.

Six weeks after herbicide was applied, organic debris was separated from the sand in each pot by suspending the debris in a stream of water and washing the debris through a nest of three, 20 cm diameter Laboratory Test Sieves with apertures of 1.5 mm, 1.0 mm and 38 µm, respectively. The washing process was repeated until all debris was removed from the sand. For the clover treatments, the debris on each of the three sieves from each pot was combined and resuspended in 250 mL of tap water and macerated in commercial blender at low speed for 30 sec. The numbers of hyphal fragments, monilioid cells and sclerotia were counted at 160X magnification in five, one mL aliquots of the macerated suspension per pot and totals per 10 g, 100 g and 100 g, respectively, of sand calculated. For the grass treatments, the procedure was the same, except that the root mass from each pot was excluded because of their bulk. The root system of each of four plants from each pot from the + and - herbicide treatments was examined at 160X magnification and the number of hyphal fragments, fragments of monilioid cells and numbers of sclerotia recorded.

The data of counts in water suspensions were analysed by analysis of variance (ANOVA, Genstat for Windows 5<sup>th</sup> Edition ™; Lawes Agricultural Trust, Rothamsted Experimental Station) as a split/split plot design. Fungal isolate was the main treatment and plant species and herbicide application were the sub-treatments. The analysis was done on square root transformed data. The data from grass roots was analysed by ANOVA.

## Results

The AG 2-1 isolate was pathogenic to white clover plants causing symptoms of hypocotyl rot and damping-off just after seedling emergence and symptoms of 'wire stem' at the rosette forming stage in older plants. The AG3 isolate was not pathogenic to clover. Neither of the isolates was pathogenic to perennial ryegrass.

The *R. solani* AG3 and AG2-1 isolates developed hyphae, monilioid cells and sclerotia in presence of grass and clover roots (Table 42 and Table 43). Overall, the most abundant numbers of hyphal fragments, monilioid cells and sclerotia were those of *R. solani* AG3 in clover treated with herbicide.

Greater numbers of sclerotia, monilioid cells and hyphal fragments of *R. solani* AG3 were found in sprayed than in unsprayed clover ( $P=0.061$ , 0.027 and 0.05, respectively) (Table 42). For *R. solani* AG2-1, there were generally no significant differences ( $P>0.05$ ) in the numbers of sclerotia, monilioid cells and hyphal fragments in clover.

In the grass treatments, there were no significant differences ( $P>0.05$ ) in the numbers of the different survival forms of *R. solani* AG3 between herbicide and non-herbicide treatments. However, a trend in the data indicated fewer sclerotia, monilioid cells and hyphal fragments in the sprayed compared with the unsprayed treatments (Table 42). A similar, though non-significant trend also occurred for numbers of the different survival forms in the grass root mass (Table 43). For *R. solani* AG2-1, there were more sclerotia and hyphal fragments in the sprayed compared with the unsprayed treatment ( $P\leq 0.061$  and 0.05, respectively), with a similar, though non-significant trend for monilioid cells (Table 42). These differences were not apparent in the root mass of grass grown with *R. solani* AG2-1 (Table 43).

## Discussion

Survival forms of *R. solani* AG3 and AG2-1 (melanised hyphal fragments, monilioid cells and sclerotia) were found in perennial ryegrass and white clover in artificially inoculated pots, irrespective of herbicide treatment. The glyphosate treatment resulted in significantly greater numbers of survival forms of *R. solani* AG3 in clover and *R. solani* AG2-1 in grass but had no apparent effect on the AG3 isolate in grass, or on the AG2-1 isolate in clover. This preliminary experiment demonstrates the potential of chemical fallowing of pasture species to affect soil inoculum of both strains of *R. solani*. This has implications for the methods of seed-bed preparation. However, more detailed studies are needed to understand the interaction between the different strains of *R. solani*, the host species and type of herbicide so that the effects of chemical fallowing can be predicted. The apparent contradictions in the effects of the herbicide treatment between AG3 and AG2-1 may relate to the differences in the relationship between the two isolates and the different hosts, or in relative differences in their activity as saprophytes.

Both *R. solani* AG3 and AG2-1 can produce sclerotia in soil (Naiki and Ui 1978), as well as on the surfaces of the roots of various plant species grown in rotation with potatoes in Australia (Section 4.4). Herbicides could have both direct and indirect effects on plant pathogens. One study reported differences in the number and size of sclerotia of different anastomosis groups of *R. solani* in soil treated with different herbicides (Harikrishnan 2001). Herbicides may affect the physiology of target plant species and this in turn could affect the activity *R. solani* on the roots. The production of sclerotia on potato tubers stimulated by the chemical destruction of the plant haulm is governed by changes in exudates from the tuber skin (Dijst 1989). A similar process may occur on plant roots treated with herbicides.

The experiment reported here was conducted under highly artificial conditions. Furthermore, the activity of *R. solani* in potatoes with or without herbicides was not tested here and the effect of natural senescence on the relationship between *R. solani* and its host was also not tested here. This work should be repeated under conditions more closely related to the natural

environment of the potato field to more accurately determine the effect of herbicide treatments on populations of the fungus.

**Table 42 Effects of spraying-off perennial ryegrass and white clover plants with the herbicide glyphosate on the production of survival forms of *Rhizoctonia solani* AG3 and AG2-1 in soil and on roots in a glasshouse experiment**

<i>R. solani</i> AG isolate	Pasture spp.	Her- bicide	No. hyphal fragments/10g sand Sqr <sup>A</sup>	No. monilioid cells/100 g sand Sqr <sup>A</sup>	No. sclerotia/100 g sand	Sqr <sup>A</sup>
AG3	Clover	+	30.25	5.55	278.56	16.69
	Clover	-	15.05	3.88	52.27	7.23
AG2-1	Clover	+	5.06	2.25	5.02	2.24
	Clover	-	6.76	2.60	7.29	2.70
AG3	Grass	+	3.42	1.85	41.60	6.45
	Grass	-	9.24	3.04	121.22	11.01
AG2-1	Grass	+	18.49	4.30	22.47	4.74
	Grass	-	0.71	0.84	1.25	1.12
F-test P value			-	<0.001	-	0.027
l.s.d (P=0.05)			-	1.700	-	7.024
					-	0.061
					-	3.295

<sup>A</sup> Statistical analysis was done on square root transformed data

**Table 43 Effects of spraying-off perennial ryegrass plants on the number of hyphae fragments, monilioid cells and sclerotia in the root mass of perennial ryegrass plants in a glasshouse experiment**

Root mass	<i>R. solani</i> AG isolate	Herbicide	No. hyphae fragments in root mass/pot	No. monilioid cells in root mass/pot	No. sclerotia in root mass/pot	
			Square root <sup>A</sup>	Square root <sup>A</sup>	Square root <sup>A</sup>	
Grass	AG3	+	25.44	3.91	7.06	1.87
Grass	AG3	-	57.31	7.04	8.5	2.66
Grass	AG2-1	+	18.00	3.50	0.75	0.43
Grass	AG2-1	-	19.00	4.16	0.00	0.00
F-test P value			-	0.494	-	0.503
l.s.d. (P=0.05)			-	n.s.	-	n.s.
					-	n.s.

<sup>A</sup> Statistical analysis was done on square root transformed data

## 4.6 Technology Transfer

### Communication with growers and the industry

The results of this project have been presented to growers across Southern Australia through workshops, seminars and field days. Details of many of the presentations are listed below.

- Field Day - Bullarook, Victoria, 29 March 1996
- Grower Seminar - Thorpdale, Victoria, 18 February 1997
- Field Day - Strathalbyn South Australia, 5 March 1997
- Field Day - Demonstration Farm, Bullarook, 18 March 1997
- Information Evening - Ballarat, Victoria, 27 October 1997
- Field Walk - Demonstration Farm, Bullarook, 19 December 1997
- Grower Seminar - Virginia Potato Growers Association, Virginia, South Australia, January 1998
- Field Day - Demonstration Farm, Bullarook, Victoria 20 March 1998
- Biofumigation Workshop - Demonstration Farm, Bullarook, 14 September 1998
- Seed Potato Industry Workshop - Colac, 16-17 September 1998
- National Potato Field Day - Institute for Horticultural Development Toolangi, 18 February 1999
- Series of Grower Meetings - Tasmania, 18-19 June 1999
- Series of Grower Information Sessions, - Perth, Bunbury, Manjimup, Albany, Western Australia, October 1999
- Series of half-day workshops held for Victorian Seed Growers – Thorpdale, Ballarat, Gellibrand, Portland, 9, 10, 16 and 17 November 1999
- Potatoes 2000 - Linking Research to Practice. Australian Potato Research, Development and Technology Transfer, Adelaide, 31 July – 3 August 2000
- Potato Growers Seminar - CHIPS Demonstration Farm, Bullarook, 10 August 2000
- Potato Growers Seminar - CHIPS Demonstration Farm, Bullarook, 22 August 2001
- Potato Growers Seminar - CHIPS Demonstration Farm, Bullarook, 27 August 2002
- Grower workshops, Colac, Portland and Ballarat, Victoria, 2-3 September 2002
- Grower workshops Devonport and Scottsdale, Tasmania, 7-8 October 2002
- VicSPA Certification Workshop - Toolangi, 17 January 2002

A WIN TV reporter and camera crew filmed a story on biofumigation in a grower's field on the Bellarine Peninsula, near Geelong. The storey involved a discussion between a fresh market grower, Santo Spano, and the project leader about biofumigation. The grower had grown a crop of fodder *Brassica* for ploughing-in as a green manure before planting potatoes. The storey went to air on WIN TV news in rural Victoria and was used several times over a number of years across southern Australia.

### Publications arising from this project

Publications from this project include conference papers, abstracts and posters, as well as articles in industry journals and the popular press.

de Boer, R. F (1995). Crop rotation and potato diseases. Proceedings of the national Crispin Potato Industry Workshop, Mildura, Victoria, 3-5 July 1995. 43-45.

de Boer, R F. (1996). Crop rotation and potato diseases. Field notes from Field Day and Trade Display "Potatoes for quality and profit" Bullarook, 29 March 1996.

Petkowski, J.E., de Boer, R.F. (1997). Crop rotation – an old method of disease control in modern potato production. *Potato Australia* 8, 47.

"Potato trials verdict positive" Rural News, *The Courier*, Ballarat, 6 May 1998.

de Boer, R.F. Improving potato yields by reducing disease. (1998). HortReport'98. Horticultural Research Development Corporation.

Petkowski, J. and de Boer, R.F. and (1999). The effect of method and timing of seed-bed preparation on *Rhizoctonia* stem canker, black scurf and yield of potatoes. In Proceedings of the First Australian Soilborne Disease Symposium. pp 182-183. (Ed R.C. Magarey). (Bureau of Sugar Experiment Stations , Brisbane, 1999). Oral presentation at the above symposium.

Petkowski J, and de Boer, R.F. (1999). Biofumigation – a role for brassica crops in pest potato pest and disease control. Poster, 'Potatoes for Quality and Profit' Field Day, Toolangi, 18 February 1999.

Petkowski, J. and de Boer, R.F. (1999). Crop rotation and the management of soil-borne potato diseases. CHIPS Newsletter.

Seymour, L. (1999). A study of the biofumigation potential of mustard meal, derived from *Brassica juncea* 'Siroma'. Against the potato pathogens *Rhizoctonia solani* and *Colletotrichum coccodes*. 212-424 Project in Agricultural Science, Institute of Land and Food Resources, University of Melbourne.

Hearnden, P. (1999). The effect of simulated crop rotation on stem canker and black scurf of potato caused by *Rhizoctonia solani*. 212-424 Project in Agricultural Science, Institute of Land and Food Resources, University of Melbourne.

"Rotation Researched" – 'Potato practice unravelled'. *Bendigo Advertiser*, 20<sup>th</sup> June 2000

“Rotation Trials” – “Making News” *The Land*, 22th June 2000.

Petkowski, J.E., and de Boer, R.F. (2000). "Ancient solution – new science". *Shorts - short stories from the NRE Horticultural Program*. Edition No.1 May 2000. Eds Tony Allen and Joanne Bates (Department of Natural Resources and Environment, Victoria).

Wicks, T., and de Boer, R. (2000). Diseases – issues and control practices. In ‘Potatoes 2000, Linking Research to Practice. Conference Proceedings of the Australian Potato Research, Development and Technology Transfer Conference, 31 July – 3 August 2000, Adelaide, South Australia’. (Eds C.M. Williams and L.J. Walters). pp 33-34. (South Australian Research and Development Institute, South Australia).

Petkowski, J.E. and de Boer, R.F. (2000). Managing soil-borne diseases – the role of rotation and biofumigation. *Speakers notes, Potato Growers Seminar, Bullarook, 10 August 2000.*

de Boer, R.F. (2000). European Powdery Scab Workshop. *Eyes on Potatoes, Australian Potato Industry Council Newsletter*, 11, December 2000, p 5.

Pitt, A.J. and de Boer R.F. (2000). The European Powdery Scab Workshop, Aberdeen, Scotland, 20-22 July, 2000.A report for the Horticultural Research and Development Corporation and Seed Potatoes Victoria, September 2000. (Department of Natural Resources and Environment, Victoria).

de Boer, R.F. (2001). Research into the biology and control of powdery scab of potatoes in Australia. In 'Proceedings of the First European Powdery Scab Workshop, Scottish Agricultural College, Craibstone Estate, Aberdeen, Scotland, July 20-22, 2000'. (Eds Ueli Merz and Alison K. Lees). pp 79-83.

de Boer, R.F., and A.J. Pitt (2001). Powdery scab and potato production in Australia. In 'Proceedings of the First European Powdery Scab Workshop, Scottish Agricultural College, Craibstone Estate, Aberdeen, Scotland, July 20-22, 2000'. (Eds Ueli Merz and Alison K. Lees). pp 23-24.

de Boer, R.F. (2001). Summary of session on recognising the components of an integrated control approach to powdery scab and the potato mop top virus. In 'Proceedings of the First European Powdery Scab Workshop, Scottish Agricultural College, Craibstone Estate, Aberdeen, Scotland, July 20-22, 2000'. (Eds Ueli Merz and Alison K. Lees). pp 101-104.

Harding, R.B. and Wicks, T.J. (2001). Effects of incorporating brassica and cereal cover crop residues on soil populations of *Verticillium dahliae*. In 'Proceedings of the Second Australasian Soilborne Diseases Symposium, The Cumberland Resort, Lorne, Victoria, 5-8 March 2001'. (Eds I.J. Porter *et al.*), pp 148-149. (Second Australasian Soilborne Diseases Symposium, Victoria, Australia).

Harding, R.B. and Wicks, T.J. (2001). *In vitro* suppression of soilborne potato pathogens by volatiles released from brassica residues. In 'Proceedings of the Second Australasian Soilborne Diseases Symposium, The Cumberland Resort, Lorne, Victoria, 5-8 March 2001'. (Eds I.J. Porter *et al.*), pp 159-160. (Second Australasian Soilborne Diseases Symposium, Victoria, Australia).

Petkowski, J.E. and de Boer, R.F. (2001). *Rhizoctonia solani* anastomosis group AG 3 and AG 2-1 as pathogens of potatoes and other crops in potato production systems. In 'Proceedings of the Second Australasian Soilborne Diseases Symposium, The Cumberland Resort, Lorne, Victoria, 5-8 March 2001'. (Eds I.J. Porter *et al.*), pp 38-39 (Second Australasian Soilborne Diseases Symposium, Victoria, Australia).

Crump, N.S., Petkowski, J.E. and de Boer, R.F. (2001). Identification of Australian isolates of *Rhizoctonia solani* AG 3 using a SCAR marker. In 'Conference Handbook of the 13<sup>th</sup> Biennial Plant Pathology Conference of the Australasian Plant Pathology Society, Cairns, Queensland, 24-27 September 2001. (Eds Veronica Oliver, Peter Trevorrow and Richard Davis). p 169. - Poster

Petkowski, J.E. and de Boer, R.F. (2002). Know your enemy – rotation trials help unravel the Rhizoctonia story. *Potato Australia* 13. 40-42.

Petkowski JE, Czerniakowski B and de Boer RF (2003). *Rhizoctonia solani* anastomosis groups associated with potatoes in Victoria, Australia. In *Abstracts of the Horticulture Conference, Institute for Horticultural Development, Knoxfield, Victoria, 21-22 August 2002*

## 4.7 Recommendations

This project is the first major study of the influence of crop rotation on disease and yield of potatoes in Australia. It has provided a valuable insight into diseases and yields under different rotations in a number of production areas, some insights into populations of some pathogens such as *Verticillium*, *Colletotrichum* and root lesion nematodes in rotations and new and valuable insights into the complex *Rhizoctonia* fungus in our cropping systems.

Studying the effects of rotations on diseases and yields is a long-term process. A review of overseas data shows that effects of rotations tend to occur over the long-term rather than the short term. Research and Development committees will need to consider the long-term resourcing of specific research programs. Many rotational sequences can only be properly compared in trials covering several seasons. Also, because of limited resources, field trials, which very are costly, are not fully exploited for information. Integrating the activities of pathologists, agronomists, soil scientists and chemists in a program to more fully evaluate the effects of *Brassica* in rotations may have resulted in a much better understanding of the potential benefits of biofumigation and green manuring in potato production than we currently have. Interpreting the data and making sense of what is going on in field trials depends on gathering as much additional information as possible from trials.

Research into the management of soil-borne diseases is seriously hampered by our lack of knowledge of the life cycle of the potato pathogens in potato cropping systems in the Australia environment. This is partly because the techniques to do this reasonably quickly, efficiently and cost-effectively were not available in the past. New technologies are coming on stream that will revolutionise research into soil-borne diseases (e.g. Horticulture Australia Project PT01019). It is imperative that further research into disease management also includes studies of the potato pathogens. Understanding the life cycle of a pathogen, how it is affected by its environment, including the impact of rotations on pathogen populations, activity and survival, is essential to developing effective disease management strategies.

Pastures play a vital role in potato cropping. A significant proportion of the potato crop in Australia is grown after a pasture phase. If managed well, pastures can replenish soil nitrogen and restore soil structure, as well as provide value feed for livestock. However, there is anecdotal and circumstantial evidence that pasture may be a haven for pathogens causing common scab, powdery scab, pink rot and *Rhizoctonia* canker and black scurf. Results from this project indicate species of clover can host two strains of *Rhizoctonia solani* which damage the potato crop. Further studies are needed to determine the relationship between these important pathogens and the pasture, whether the pasture phase is beneficial or detrimental to their activity and reproduction and on what options there are for managing the pasture phase to ensure minimum carry-over of potato pathogens to the potato crop.

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## 4.9 References

- Adams GC (1988) *Thanatephorus cucumeris (Rhizoctonia solani)*: A species complex of wide host range . *Advances in Plant Pathology* **6**, 535-552.
- Adams MJ, Hide GA (1980) Relationships between disease levels on seed tubers, on crops during growth and in stored potatoes. 5. Seed stocks grown at Rothamsted. *Potato Research* **23**, 291-302.
- Anderson NA (1982) The genetics and pathology of *Rhizoctonia solani*. *Annual Review of Phytopathology* **20**, 329-347.
- Anguiz R, Martin C (1989) Anastomosis groups, pathogenicity, and other characteristics of *Rhizoctonia solani* isolated from potatoes in Peru. *Plant Disease* **73**, 199-201.
- Angus JF, Garner PA, Kirkegaard JA, Desmarchelier JM (1994) Biofumigation: Isothiocyanates released from *Brassica* roots inhibit growth of the take-all fungus. *Plant and Soil* **162**, 107-112.
- Balali GR, Neate SM, Scott ES, Whisson DL, Wicks TJ (1995) Anastomosis group and pathogenicity of isolates of *Rhizoctonia solani* from potato crops in South Australia . *Plant Pathology* **44**, 1050-1057.
- Bandoni RJ (1979) Safranin O as rapid nuclear stain for fungi. *Mycologia* **71**, 873-874.
- Banville GJ (1989) Yield losses and damage to potato plants caused by *Rhizoctonia solani* Kühn. *American Potato Journal* **66**, 821-834.
- Banville GJ, Carling DE, Otrysko BE (1996) Rhizoctonia disease on potato. In 'Rhizoctonia Species: Taxonomy, Ecology, Pathology and Disease Control'. (Eds B Sneh, S Jabaji-Hare, S Neate, and G Dijst) pp. 321-340. (Kluwer Academic Publishers: Dordrecht, The Netherlands)
- Barkdoll AW, Davis JR (1992) Distribution of *Colletotrichum coccodes* in Idaho and variation in pathogenicity on potato. *Plant Disease* **76**, 131-135.
- Bogucka H (1983) Effect of the inoculation of seed tubers on some potato varieties with *Rhizoctonia solani* Kuhn on the incidence of disease and the response of varieties. *Biuletyn Instytutu Ziemniaka* **30**, 85-95.
- Bollen GJ, Hoekstra O, Scholte K, Hofman TW, Celetti MJ, Schirring A (1989) Incidence of soilborne pathogens in potato related to the frequency of potato growing on a clay loam. In 'Effects of Crop Rotation on Potato Production in the Temperate Zones'. (Eds J Vos, CD van Loon, and GJ Bollen) pp. 203-222. (Kluwer Academic Publishers: Dordrecht, The Netherlands)
- Boosalis MG, Scharen AL (1959) Methods for microscopic detection of *Aphanomyces euteiches* and *Rhizoctonia solani* and for the isolation of *Rhizoctonia solani* associated with plant debris. *Phytopathology* **49**, 192-198.
- Brodie BB (2001) Potato cyst nematodes. In 'Compendium of Potato Diseases'. (Eds WR Stevenson, R Loria, GD Franc, and DP Weingartner) pp. 48-50. (The American Phytopathological Society: St Paul, Minnesota, USA)
- Brown PD, Morra MJ, McCaffrey JP, Auld DL, Williams L (1991) Allelochemicals produced during glucosinolate degradation in soil. *Journal of Chemical Ecology* **17**, 2021-2034.
- Butterfield EJ, De Vay JE (1977) Reassessment of soil assays for *Verticillium dahliae*. *Phytopathology* **67**, 1073-1078.
- Carling DE, Baird RE, Gitaitis KA, Brainard KA, Kuninaga S (2002) Characterization of AG-13, a newly reported anastomosis group of *Rhizoctonia solani*. *Phytopathology* **92**, 893-899.
- Carling DE, Kebler KM, Leiner RH (1986) Interactions between *Rhizoctonia solani* AG-3 and 27 plant species. *Plant Disease* **70**, 577-578.

- Carling DE, Kuninaga S, Leiner RH (1988) Relatedness within and among intraspecific groups of *Rhizoctonia solani*: a comparison of grouping by anastomosis and by DNA hybridization. *Phytoparasitica* **16**, 209-210.
- Carling DE, Leiner RH (1986) Isolation and characterization of *Rhizoctonia solani* and binucleate *R. solani*-like fungi from aerial stems and subterranean organs of potato plants. *Phytopathology* **76**, 725-729.
- Carling DE, Leiner RH (1990) Effect of temperature on virulence of *Rhizoctonia solani* and other *Rhizoctonia* on potato. *Phytopathology* **80**, 930-934.
- Carter M (1996) In 'Potatoes for quality and profit'. Food Crop Development Centre, Bourkes Road, Bullarook.
- Carter MR, Sanderson JB (2001) Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. *Soil and Tillage Research* **63**, 1-13.
- Celetti MJ, Johnston HW, Platt HW (1989a) Effect of clover, ryegrass and winter wheat used in rotation with potatoes on the incidence of disease and soilborne pathogens in potatoes. In 'Effects of Crop Rotation on Potato Production in the Temperate Zones'. (Eds J Vos, CD van Loon, and GJ Bollen) pp. 197-202. (Kluwer Academic Publications: Dordrecht, The Netherlands)
- Celetti MJ, Johnston HW, Platt HW (1989b) Incidence of soilborne potato pathogens in six crops used in rotation with potatoes. In 'Effects of Crop Rotation on Potato Production in the Temperate Zones'. (Eds J Vos, CD van Loon, and GJ Bollen) pp. 191-196. (Kluwer Academic Publishers: Dordrecht, The Netherlands)
- Chand T, Logan C (1982) Reaction of ten potato cultivars to stem canker and black scurf of potato caused by *Rhizoctonia solani*. *Annals of Applied Biology* **100**, 102-3.
- Chand T, Logan C (1983) Cultural and pathogenic variation in potato isolates of *Rhizoctonia solani* in Northern Ireland. *Transactions of the British Mycological Society* **81**, 585-589.
- Chang YC, Tu CC (1980) Pathogenicity of different anastomosis groups of *Rhizoctonia solani* Kühn to potatoes (Abstract). *Journal of Agricultural Research, China* **29**, 27-33.
- Christ BJ (2001) Powdery scab. In 'Compendium of Potato Diseases'. (Eds WR Stevenson, R Loria, GD Franc, and DP Weingartner) pp. 35-36. (The American Phytopathological Society: Minnesota, USA)
- Cother EJ (1979) Presence of *Rhizoctonia solani* in native *Callitris* pine soils and its implications for future potato growing. *Australasian Plant Pathology* **8**, 15-16.
- de Boer R, Wicks T (1994) Survey of black dot and other diseases of potato tubers. *Potato Australia* **5**, 40-41.
- de Boer RF (1994) Effects of tillage practices on diseases of wheat caused by soil and stubble-borne pathogens in Victoria, Australia. PhD Thesis, La Trobe University, Bundoora .
- de Boer RF (1997) Integrated management of silver scurf and black dot of potatoes. Final Report. Horticultural Research and Development Corporation Project No. PT405.
- de Boer RF, Theodore M (1997) Epidemiology and control of powdery scab of potatoes. Final Report. Horticultural Research and Development Corporation Project No. PT303.
- Dijst G (1985) Investigations on the effect of haulm destruction and additional root cutting on black scurf on potato tubers. *Netherlands Journal of Plant Pathology* **91**, 153-162.
- Dijst G (1989) The effect of chemical haulm destruction and haulm pulling on potato black scurf caused by *Rhizoctonia solani* AG-3. Wageningen Agricultural University.
- Dijst G (1990) Effect of volatile and unstable exudates from underground potato plant parts on sclerotium formation by *Rhizoctonia solani* AG3 before and after haulm destruction. *Neth. J. Plan Pathol.* **96**, 155-170.
- Dijst, Gerda and Schneider, HM (1996) Flower bulb diseases incited by *Rhizoctonia* species In 'Rhizoctonia Species: Taxonomy, Ecology, Pathology and Disease Control' (Eds. Baruch Sneh, Suha Jabaji-Hare, Stephen

Neate, and Gerda Dijst) pp. 279-288 (Kluwer Academic Publishers: Dordrecht, The Netherlands)

Dillard HR (1992) *Colletotrichum coccodes*: The pathogen and its hosts. In 'Colletotrichum: Biology, Pathology and Control'. (Eds JA Bailey and MJ Jeger) (CAB International: Wallingford, Oxon, United Kingdom)

Dillard HR, Cobb AC (1998) Survival of *Colletotrichum coccodes* in infected tomato tissue and in soil. *Plant Disease* **82**, 235-238.

Doornik A (1980) Some factors affecting the parasitic and saprophytic activity of *Rhizoctonia solani*. In Third International Symposium of Flower Bulbs'. Nyborg, Denmark. (Ed. E Rasmussen) pp. 387-391. (International Society for Horticultural Science: The Hague, The Netherlands)

Doornik A (1981) Temperature dependence of the pathogenicity of several isolates of *Rhizoctonia solani* in some bulb crops as an intrinsic property of the isolate. *Netherlands Journal of Plant Pathology* **87**, 139-147.

Ellington A (1986) Nitrogen inputs and utilisation in leguminous pasture: a review of recent Australian literature. Technical Report Series No 128, June 1986, Department of Agriculture and Rural Affairs, Victoria, 19 pp.

Fenwick GR, Heaney RK, Mullin WJ (1983) Glucosinolates and their breakdown in food and food plants. *Critical Review of Food Science and Nutrition*. **18**, 123-201.

Frank JA (1978) The *Rhizoctonia* disease of potatoes in Maine. *American Potato Journal* **55**, 59.

Frank JA, Murphy HJ (1977) The effect of crop rotation on Rhizoctonia disease of potatoes. *American Potato Journal* **54**, 315-322.

Gilligan C, Simons S, Hide G (1996) Inoculum density and spatial pattern of *Rhizoctonia solani* in field plots of *Solanum tuberosum*: effects of cropping frequency. *Plant Pathology* **45**, 232-244.

Glass E, Thurston H (1978) Traditional and modern crop protection in perspective. *Bioscience* **28**, 109-115.

Gudmestad NC, Huguelet JE, Zink RT (1978) The effect of cultural practices and straw incorporation into the soil on Rhizoctonia disease of potato. *Plant Disease Reporter* **62**, 985-989.

Gudmestad NC, Stack R, Salas B (1989) Colonization of potato by *Rhizoctonia solani* as affected by crop rotation . In 'Effects of Crop Rotation on Potato Production in the Temperate Zones'. (Eds J Vos, C van Loon, and G Bollen) pp. 247-252. (Kluwer Academic Publishers: Dordrecht, The Netherlands)

Harikrishnan RYXB (2001) Influence of herbicides on growth and sclerotia production in *Rhizoctonia solani*. *Weed Science* **49**, 241-247.

Harrison DE (1963) Black dot disease of potato. *The Journal of the Department of Agriculture, Victoria* **61**, 573-576.

Hide GA, Hirst JM, Stedman OJ (1973) Effects of black scurf (*Rhizoctonia solani*) on potatoes. *Annals of Applied Biology* **74**, 139-148.

Hide GA, Read PJ, Firmager JP, Hall SM (1989a) Stem canker (*Rhizoctonia solani*) on five early and seven main crop potato cultivars: I. Infection of shoots, stolons and tubers. *Annals of Applied Biology* **114**, 255-265.

Hide GA, Read PJ, Firmager JP, Hall SM (1989b) Stem canker (*Rhizoctonia solani*) on five early and seven main crop potato cultivars. II. Effects on growth and yield. *Annals of Applied Biology* **114**, 267-277.

Hilton A, Kyritsis, P (2001) Rhizoctonia on the rampage. Potato Newsletter [September 2001], 16-17. 2001. Scottish Agricultural College, Aberdeen, Scotland, UK (British Potato Council).

Hoekstra, O. (1981) De Schreef Resultaten van 15 jaar vruchtwisselingsonderzoek op het bouwplannenproefveld De Schreef. Proefstation voor de Akkerbouw en Groenteteelt in de Velle grond (Lelystad, Netherlands) **11**, 1-93.

- Hooper EJ, Evans K (1993) Extraction, identification and control of plant parasitic nematodes. In 'Plant and Parasitic Nematodes in Temperate Agriculture'. pp. 1-19.
- Hwong S, Howard RJ, Chang K (1996) Forage and oilseed legume diseases incited by *Rhizoctonia* species. In 'Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and Disease Control'. (Eds B Sneh, S Jabaji-Hare, S Neate, and G Dijst) pp. 289-301. (Kluwer Academic Publishers: Dordrecht, The Netherlands)
- Isbell RF (1996) 'The Australian soil classification.' (CSIRO Publishing: 150 Oxford Street, Collingwood, Victoria, Australia)
- Jager G, Hekman W, Deenen A (1982) The occurrence of *Rhizoctonia solani* on subterranean parts of wild plants in the potato field. *Netherlands Journal of Plant Pathology* **88**, 155-161.
- Jager G, Velvis H (1995) Dynamics of *Rhizoctonia solani* (black scurf) in successive potato crops. *European Journal of Plant Pathology* **101**, 467-478.
- James WC, McKenzie AR (1972) The effect of tuber-borne sclerotia of *Rhizoctonia solani* Kuhn on the potato crop. *American Potato Journal* **46**, 296-301.
- Keller ER (1989) Crop rotation - an important aspect in integrated potato production. In 'Effects of Crop Rotation on Potato Production in the Temperate Zones'. (Eds J Vos, CD Van Loon, and GJ Bollen) pp. 291-301. (Kluwer Academic Publications: Dordrecht, The Netherlands)
- Khangura R, Barbetti M, Sweetingham M (1999) Characterization and pathogenicity of Rhizoctonia species on canola. *Plant Disease* **83**, 714-721.
- Kirkegaard JA, Sarwar M (1998) Biofumigation potential of brassicas. I. Variation in glucosinolate profiles of diverse field-grown brassicas. *Plant and Soil* **201**, 71-89.
- Kirkegaard JA, Sarwar M, Wong PTW, Mead A (1998) Biofumigation by brassicas reduces Take-all infection. In 'Proceedings of the Ninth Australian Agronomy Conference'. Charles Sturt University, Wagga Wagga, NSW. (Eds DL Michalik and JE Pratley) pp. 465-468. (The Australian Society of Agronomy).
- Kirkegaard JA, Wong PTW, Desmarchelier JM (1996) *In vitro* suppression of fungal root pathogens of cereals by *Brassica* tissues. *Plant Pathology* **45**, 593-603.
- Lamers JG, Hoekstra O, Scholte K (1989) Relative performance of potato cultivars in short rotations. In 'Effects of Crop Rotation on Potato Production in the Temperate Zones'. (Eds J Vos, C van Loon, and G Bollen) pp. 57-65. (Kluwer Academic Publishers: Dordrecht, The Netherlands)
- Leach SS, Porter GA, Rourke RV, Clapham WM (1993) Effects of moldboard plowing, chisel ploughing and rotation crops on the Rhizoctonia disease of white potato. *American Potato Journal* **70**, 329-337.
- Liu ZL, Sinclair JB (1992) Genetic diversity of *Rhizoctonia solani* anastomosis group 2. *Phytopathology* **80**, 778-787.
- Mayton HS, Oliver C, Vaughn SF, Loria R (1996) Correlation of fungicidal activity of *Brassica* species with allyl isothiocyanate production in macerated leaf tissue. *Phytopathology* **86**, 267-271.
- Mazzola M, Smiley RW, Rovira AD, Cook JR (1996) Characterization of *Rhizoctonia* isolates, disease occurrence and management in cereals. In 'Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and Disease Control'. (Eds B Sneh, S Jabaji-Hare, S Neate, and G Dijst) pp. 259-267. (Kluwer Academic Publishers: Dordrecht, The Netherlands)
- McDonald HJ, Rovira A D (1985) Development of inoculation technique for *Rhizoctonia solani* and its application to screening cereal cultivars for resistance. In 'Proceedings of Section 5 of the Fourth International Congress of Plant Pathology'. University of Melbourne, Melbourne, Australia. (Eds CA Parker, KJ Rovira, KJ Moore, and PTW Wong) pp. 174-176. (The American Phytopathological Society, St Paul, Minnesota, USA)
- Merida CL, Loria R (1994) Survival of *Helminthosporium solani* in soil and *in vitro* colonization of senescent plant tissue. *American Potato Journal* **71**, 591-598.

- Naiki T, Ui T (1978) Ecological and morphological characteristics of the sclerotia of *Rhizoctonia solani* Kühn produced in soil. *Soil Biology and Biochemistry* **10**, 471-478.
- Ogoshi A (1987) Ecology and pathogenicity of anastomosis and intraspecific groups of *Rhizoctonia solani* Kühn. *Annual Review of Phytopathology* **25**, 125-143.
- Papavizas GC (1968) Survival of root infecting fungi in soil. VIII. Distribution of *Rhizoctonia solani* in soil in various fractions of naturally and artificially infested soils. *Phytopathology* **58**, 746-751.
- Papavizas GC, Adams PB, Lumsden RD, Lewis JA, Dow RL, Ayers WA, Kantzes JG (1975) Ecology and epidemiology of *Rhizoctonia solani* in field soil. *Phytopathology* **65**, 871-877.
- Papavizas GC (1970) Colonization and growth of *Rhizoctonia solani* in soil In 'Rhizoctonia solani: Biology and Pathology' pp. 108-122 (University of California Press: Berkeley, USA)
- Papavizas G, Davey C (1962) Isolation and pathogenicity of *Rhizoctonia* saprophytically existing in soil. *Phytopathology* **52**, 834-840.
- Parmenter JRJ, Sherwood RT, Platt WD (1969) Anastomosis grouping among isolates of *Thanatephorus cucumeris*. *Phytopathology* **57**, 127-1278.
- Petkowski JE, de Boer RF (2001) *Rhizoctonia solani* anastomosis group AG3 and AG2-1 as pathogens of potato and other crops in potato production systems. In 'Proceedings of the Second Australasian Soilborne Diseases Symposium'. Lorne, Victoria, Australia.
- Potter MJ, Davies K, Rathjen AJ (1998) Suppressive impact of glucosinolates in *Brassica* vegetative tissues on root lesion nematode *Pratylenchus neglectus*. *Journal of Chemical Ecology* **24**, 67-80.
- Potter MJ, Vanstone V A, Davies KA, Kirkegaard JA (1999) Reduced susceptibility of *Brassica napus* to *Pratylenchus neglectus* in plants with elevated root levels of 2-phenylethyl glucosinolate. *Journal of Nematology* **31**, 291-298.
- Powelson M (2001) White Mould. In 'Compendium of Potato Diseases'. (Eds WR Stevenson, R Loria, GD Franc, and D Weingartner) (American Phytopathological Society: St Paul, Minnesota, USA)
- Raid RN, Pennypacker SP (1987) Weeds as hosts for *Colletotrichum coccodes*. *Plant Disease* **71**, 643-646.
- Read PJ, Hide GA, Firmager JP, Hall SM (1989) Growth and yield of potatoes as affected by severity of stem canker (*Rhizoctonia solani*). *Potato Research* **32**, 9-15.
- Roget DK, Venn NR, Rovira AD (1987) Reduction of Rhizoctonia root rot of direct-drilled wheat by short term chemical fallow. *Australian Journal of Experimental Agriculture* **27**, 425-430.
- Sarwar M, Kirkegaard JA (1998) Biofumigation potential of brassicas. II. Effect of environment and ontogeny on glucosinolate production and implications for screening. *Plant and Soil* **201**, 91-101.
- Sarwar M, Kirkegaard JA, Wong PTW, Desmarchelier JM (1998) Biofumigation potential of brassicas. III. *In vitro* toxicity of isothiocyanates to soil-borne fungal pathogens. *Plant and Soil* **201**, 103-112.
- Scholte K (1987) The effect of crop rotation and granular nematicides on the incidence of *Rhizoctonia solani* in potato. *Potato research* **30**, 187-199.
- Scholte K (1992) Effect of crop rotation on the incidence of soil-borne fungal diseases of potato. *Netherlands Journal of Plant Pathology* **98**, 93-101.
- Sieczka JB (1989) Some negative aspects of crop rotation. In 'Effects of Crop Rotation on Potato Production in the Temperate Zones'. (Eds J Vos, CD Van Loon, and GJ Bollen) pp. 259-272. (Kluwer Academic Publications: Dordrecht, The Netherlands)
- Simons SA, Gilligan CA (1997) Relationships between stem canker, stolon canker, black scurf (*Rhizoctonia solani*) and yield of potato (*Solanum tuberosum*) under different agronomic conditions. *Plant Pathology* **46**,

651-658.

Small T (1943) Black scurf and stem canker of potatoes (*Corticium solani* Boud. & Galz.). Field studies on the use of clean and contaminated seed potatoes and on the contamination of crop tubers. *Annals of Applied Biology* **30**, 221-226.

Small T (1945) Black scurf and stem canker of potatoes (*Corticium solani* Boud. & Galz.) Further field studies on the use of clean and contaminated seed potatoes and on the contamination of crop tubers. *Annals of Applied Biology* **32**, 206-209.

Sneh B, Burpee L, Ogoshi A (1991) Identification of *Rhizoctonia* Species.' (The American Phytopathological Society: St Paul, Minnesota, USA)

Sneh B, Jabaji-Hare S, Neate S, Dijst G (1996) 'Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and Disease Control.' (Kluwer Academic Publishers: Dordrecht, The Netherlands)

Sorensen LH, Schneider AT, Davis JR (1991) Influence of sodium polygalacturonate sources and improved recovery of *Verticillium* spp from the soil. *Phytopathology* **81**, 134-137.

Specht LP, Leach SS (1987) Effects of crop rotation on *Rhizoctonia* disease of white potato. *Plant Disease* **71**, 433-437.

Sturz AV, Carter MR, Johnston HW (1997) A review of plant disease, pathogen interactions and microbial antagonism under conservation tillage in temperate humid agriculture. *Soil and tillage research* **41**, 169-189.

Thornton R (2001) High-temperature injury to stems and foliage. In 'Compendium of Potato Diseases'. (Eds WR Stevenson, R Loria, GD Franc, and D Weingartner) p. 81. (American Phytopathological Society: St Paul, Minnesota, USA)

Van Emden JH (1966) Bijdrage tot de kennis van de Rhizoctonia ziekte in de Nederlandse pootaardepelteelt. *Mededeling nr. 412 van het Instituut voor Plantenziektenkundig Onderzoek*.

van Loon CD (1992) Integrated crop management, the basis for environment friendly crop protection of potatoes. *Netherlands Journal of Plant Pathology* **98**, 231-240.

van Overbeek LS, Cassidy M, Kozdroj J, Trevors JT, van Elsas JD (2002) A polyphasic approach for studying the interaction between *Ralstonia solanacearum* and potential control agents in the tomato phytosphere. *Journal of Microbiological Methods* **48**, 69-86.

Virgen-Calleros G, Olalde-Portugal V, Carling DE (2000) Anastomosis groups of *Rhizoctonia solani* on potato in central Mexico and potential for biological and chemical control. *American Journal of Potato Research* **77**, 219-224.

Vos J, Van Loon CD (1989) Effects of cropping frequency on potato production. In 'Effects of Crop Rotation on Potato Production in the Temperate Zones'. (Eds J Vos, CD Van Loon, and GJ Bollen) pp. 1-23. (Kluwer Academic Publications: Dordrecht, The Netherlands)

Weinhold AR, Bowman T, Hall DH (1982) Rhizoctonia disease of potato: effect on yield and control by seed tuber treatment. *Plant Disease* **66**, 815-818.

Wong DH, Sivasithamparam K (1985) *Rhizoctonia* spp. associated with root rots of subterranean clover in Western Australia. *Transactions of the British Mycological Society* **85**, 21-27.