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Epidemiology and control of powdery scab of potatoes

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Agriculture Victoria

Know-how for Horticulture™

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1. Industry Summary

Alternative hosts and rotation

In tests under controlled conditions in the glasshouse, the fungus causing powdery scab, *Spongospora subterranea*, infected the roots of several species of plants grown in rotation with potatoes. The severity of infection was highest on the roots of tomato seedlings used as controls, lowest on wheat, barley, perennial ryegrass, linola, 'Rangi' rape and 'York globe' turnip and intermediate on canola and 'Pasja' rape. The roots of oats and white and subterranean clovers were not infected in this study, although previous research had shown that white, subterranean, red and cluster clovers and oats are also alternative hosts.

Only an intermediate stage of the life-cycle of the fungus (zoosporangia) developed on roots of test plants. Root galls containing spore balls, the long-term survival spores of the fungus, did not develop on alternative hosts and this meant that the fungus could not complete its life-cycle. Galls are common on potato roots but are occasionally found only on the roots of close relatives of the potato (tomatoes and nightshade). Studies indicate so far that alternative hosts are unlikely to play a major role in the survival of *Spongospora* in the period between potato crops but further work is needed to confirm this.

Initial experiments showed that a bioassay using tomato seedlings could potentially be developed as a research tool to study the effect of control strategies on the populations of the pathogen in soil.

The incidence and severity of powdery scab was not influenced by different cropping sequences in five-year rotations in two field trials. The large numbers of volunteer potatoes and the ability of spores of *Spongospora* to remain dormant for several years help the fungus maintain its population in soils. Despite this, rotations with effective control of volunteer potatoes, are critical in preventing the build-up of excessive population levels of *Spongospora* in soil. Rotation and cropping practices that damage soil structure or raise soil pH (by applications of lime) could have a high risk of powdery scab.

Chemical control

Pre-plant fumigation of a volcanic loam in the Central Highlands of Victoria with metham sodium did not reduce the incidence or severity of powdery scab and other diseases or improve yield and quality of tubers. Coarse soil structure, high organic matter and clay content of soil reduced the effectiveness of the treatment. Because very high rates of application are probably required fumigation is not a economic proposition in this area. However, metham sodium fumigation warrants further evaluation in other areas. The treatment reduced the incidence and severity of powdery scab in trials in South Australia and the USA and is used to manage other major soil-borne pathogens in a range of soil types in Australia.

Six chemical pre-plant treatments, including the new fungicides fluazinam and flusulfamide, sprayed onto the surface and rotary hoed into a sandy soil at a site with high disease pressure, did not significantly reduce the incidence and severity of powdery scab on the winter grown, fresh market varieties Snowgem and Sequoia at Torquay Victoria. Many of the treatments tested had shown good control of soil-borne powdery scab in trials in Australia, New Zealand and the United Kingdom. For example, applications of fluazinam resulted in four fold increases in marketable yields in trials in Victoria. The lack of control at Torquay may have been be due to the method of application (sprayed over the entire plot rather than banded in the furrow) resulting in lower than optimum rates of fungicides, and the possible leaching of chemicals from soil during the interval between planting and emergence (8-12 weeks). Further research is needed to identify the best timing, method and rate of application of fungicides on susceptible and tolerant cultivars in different soil types, climates and disease pressures. An experimental fungicide, ICIA5504, reduced the incidence of black dot and black scurf on tubers harvested from the Torquay trial.

A preliminary glasshouse trial showed that the treatment of seed potatoes with disinfectant or protectant fungicides could reduce the carry-over of powdery scab to progeny tubers but further work is needed to develop effective seed treatments.

Controlling powdery scab - integrated management

Minimising the risk of severe outbreaks of powdery scab involves the integration of several strategies, including use of long rotations, tolerant cultivars, hygiene, chemical seed treatments, soil chemical treatments, irrigation management and perhaps modification of soil pH. There is no single method of controlling the disease. The results of trials showed that the use of tolerant cultivars is the most effective management strategy for powdery scab. Substantial improvements in the control of powdery scab in future will depend on more effective fungicide treatments, both for seed and soil-borne scab, and in the long-term, the development of cultivars with a high degree of tolerance to the disease.

2. Technical Summary

Of 16 rotation crops tested as alternative hosts to the powdery scab fungus, *Spongospora subterranea,* under controlled glasshouse conditions, 11 became infected. The severity of root infection (abundance of zoosporangia) was greatest on the tomato seedlings used as controls ('Roma', 'UC82B'), lowest on barley, wheat, linola, ryegrass ('Ellett', 'Nui'), 'York Globe' turnip and `Ranji' rape and intermediate on canola and `Pasja' rape. The fungus was not detected on the roots of oats, lucerne, ryecorn, white clover or subterranean clover. By contrast, in earlier studies (de Boer 1984), oats, lucerne, subterranean and white clover were infected, as well as red clover, cluster clover and cocksfoot. This discrepancy may be due to differences in test conditions, plant age and methods of spore ball preparation.

Spongospora galls with cystosori (spore balls), which are common on potato roots, were not found on the roots of the test seedlings. Although galls have been reported to occur on the roots of several species of Solanaceae under controlled glasshouse conditions elsewhere, they have seldom been found in the field. Without this stage, the fungus does not complete its life-cycle.

A good correlation between the number of cystosori of *S. subterranea* and the severity of primary infection on roots of tomato seedlings was recorded in a study to develop a bioassay for powdery scab in soils. Potentially a biossay could be a useful research tool for measuring the effects of various control strategies on populations of the fungus in soil.

The incidence and severity of powdery scab was not influenced by different cropping sequences after pasture (5-year rotation) in two field trials. Rotations included mixed (grass and clover) pasture, grass pastures in which clovers were selectively removed with herbicides, or sequences of pasture-ryecorn-sudax-ryecorn or pasture-ryecorn-fodder rape-ryecorn prior to cropping with potatoes. The effect of rotations on fungal inoculum may be masked by the ability of the fungus to multiply on the roots of potatoes before tuber initiation.

Studies thus far suggest that rotations may not have a significant influence on populations of *S. subterranea* in soil but further work is need to confirm this. Spores of the fungus can remain dormant in soil for many years and therefore long breaks between potatoes are required before populations decline. Relatively long rotations, with effective control of volunteer potatoes and other Solanaceous weeds, are essential in minimising the build-up of populations of the fungus, especially in potatoes cropped in new ground. Rotational practices that reduce soil drainage and raise pH could increase the risk of powdery scab. *Brassica* crops, which release natural fumigants, could potentially reduce the incidence of powdery scab but extensive evaluation in the field is needed.

Pre-planting fumigation of a volcanic loam with metham sodium did not reduce the incidence or severity of powdery scab, silver scurf or black dot on Russet Burbank, Coliban and Kennebec potatoes, nor increase the yield of Russet Burbank. The study indicates that this form of fumigation is not an economically viable for disease control in the Central Highlands region of Victoria where high organic matter content, clay content, and coarse tilth of soil can reduce the effectiveness of the treatment. However, metham sodium fumigation has been reported to reduce the incidence of powdery scab in trials in South Australia and the USA.

Six preplant chemical treatments, applied to the surface and rotary hoed into a sandy soil at a site with high disease pressure, did not significantly affect the incidence and severity of powdery scab on winter planted, fresh market potatoes. The use of a tolerant cultivar was the most effective control with an average of 18% of the progeny of Snowgem affected with powdery scab compared with 49% of the Sequoia tubers. The fungicide, fluazinam, slightly reduced the proportion of Sequoia tubers with powdery scab but had no effect on the severity of scab on Sequoia, nor on the incidence and severity of the disease on Snowgem. Additional disease assessments showed that no fungicide reduced the incidence of tubers with common scab (*Streptomyces scabies*) (37% of Snowgem and 77% of Sequoia affected) or silver scurf (*Helminthosporium solani*). An experimental fungicide, ICI5504, reduced the incidence and severity of black dot (*Colletotrichum coccodes*) on Sequoia and black scurf (*Rhizoctonia solani*) on Snowgem. Most of the fungicides tested had shown good control of powdery scab in trials elsewhere in Victoria and overseas. Lack of control at Torquay may have been due the method of application (sprayed over the entire plot surface rather than banding in the furrow) resulting in less than optimum rates, and possible leaching of chemicals during the interval between planting and emergence (8-12 weeks).

A preliminary glasshouse trial showed that the treatment of seed potatoes with disinfectant or protectant fungicides could reduce the carry-over of powdery scab to progeny tubers but further work is needed to develop effective seed treatments.

3. Recommendations

Powdery scab has proven to be a difficult disease to control. Effective management is exacerbated by the widespread contamination of soils in traditional production areas and the continued reliance by most sectors of the industry on highly susceptible cultivars. The disease must be managed by integrating a number of different strategies; there is no single method for control. Substantial improvements in the control of powdery scab will depend on the development of more effective fungicide treatments in the short-term and, in the long-term, on the development of tolerant or resistant cultivars.

Recommendations for further research or allocation of resources include:

Cultivar resistance

In the long-term, the most cost-effective and environmentally safe way of controlling powdery scab is to develop resistant cultivars. Experiments in which tolerant and susceptible cultivars where grown side-by-side (e.g. Russet Burbank *vs.* Kennebec and Coliban or Snowgem *vs.* Sequoia) clearly demonstrated the advantages of using cultivars with a high degree of tolerance.

Resistance to powdery scab is heritable but little is known of its genetic basis. Further research should involve

- effective screening of current breeding and evaluation lines under controlled conditions to ensure that only the most tolerant cultivars are released,
- incorporation of heritable resistance into new cultivars through a breeding program and
- studies to determine the physical mechanisms of resistance and the physiological, biochemical and genetic basis for resistance.

Chemical control

There are no fungicides registered for the control of powdery scab. In spite of poor control with fungicides in our study, replicated trials in Victoria and overseas indicates that these fungicides (in particular fluazinam and flusulfamide), and potentially some disinfectant products, can provide useful levels of control of seed and soil-borne powdery scab. The treatments tested at Torquay did not control the disease, perhaps because of the very high disease pressure, the method of application, and associated with that, a lower than optimum rate, and the probable leaching of fungicides from the soil because of long delay in emergence. Further work with chemical control should

- evaluate disinfestation and chemical protectant treatments for seed potatoes

- evaluate more strategic methods of applications and rates of fungicides on both susceptible and relatively tolerant cultivars over a range of conditions of soil inoculum levels, soil types, climates and crop management regimes to determine where chemical treatments are the most cost effective in an integrated management system for powdery scab.

Rotation

Further work is needed to

- understand the role of plant species other than potato in the survival of the pathogen in the period between each potato crop,
- evaluate the development of galls with spore balls on weed hosts in the field and
- evaluate the potential of biofumigation as a control strategy for powdery scab

Irrigation

Research has demonstrated a clear relationship between irrigation and the development of powdery scab in a crop. In cropping areas where there is not a high risk of rain during early tuber set there is scope for managing irrigation to control the disease. More work is required on the

- options of managing the timing, quantity and frequency of watering at early tuber set to minimise the risk of powdery scab.

Information - technological transfer

Growers require information packages on powdery scab. A thorough understanding of the organism, its biology and the *risk factors* that affect the development of disease is needed. This will help growers make informed decisions during the day-to-day management of the farm and the crop to integrate various control strategies to minimise the risk of powdery scab. Since the development of scab cannot be predicted with any certainty the management of the disease is essentially a process of risk management.

4. Extension and Publications

Presentations on powdery scab - seminars, grower talks, shed nights, fields days, conferences, workshops

February 95	National Potato Field Day Toolangi, Seminar
April 95	Crisping Potato Growers Research Group Shed Night, Corra Lynn
April 95	Crisping Potato Growers Research Group, Shed Night, Colac
August 95	National Crisping Potato Industry Workshop, Mildura
September 95	Workshop for Processing Growers, Ballarat
March 96	Field Day, Food Crop Development Centre Demonstration Farm, Ballarat
July 96	AUSVEG Conference, Brisbane
July 96	IAMA Industry Day, IHD Knoxfield
July 96	Crisping Potato Growers Research Group Seminars, IHD Knoxfield
August 96	Robertson District Potato Advancement and Landcare Association & the Crookwell Potato Growers Association, Robertson
August 96	Powdery scab 'trouble shooting' for the Crookwell Seed Potato Growers Association, Crookwell
September 96	Seed Potato Industry Trust Fund Seminars, Perth and Manjimup
September 96	Seed Potato Industry Workshop, Ballarat
February 97	Crisping Potato Growers Research Group, Farm Walk and Shed Night
March 97	Food Crop Development Centre Demonstration Farm, Ballarat

Publications

Theodore, M. (1995). What's new with powdery scab of potatoes? National Potato Field Day, Field Day Notes, February 1995.

de Boer, R.F. and Theodore, M (1995). Powdery scab - can it be controlled? *Potato Australia* **6**, 45-46.

Theodore, M (1996). Options for management of powdery scab. Field Day Handout, Ballarat Demonstration Farm, March 1996

Theodore, M, de Boer, R.F. and Hepworth, G. (1996). Evaluation of chemical treatments for the control of soil-borne powdery scab (*Spongospora subterranea*) of fresh market potatoes in a field trial at Torquay Victoria, 1995/96. *Report to Crop Care (Australia) Pty Ltd., October 1996.*

5. Acknowledgments

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6. Technical Report

6.1 Introduction

Powdery scab, caused by the fungus *Spongospora subterranea*, is a major disease of potatoes in Australia. Symptoms include the characteristic powdery or corky 'scabs' or pustules on the tuber surface and galls or 'nodules' on the roots, stolons and underground stems. From an economic point of view, powdery scab is primarily a blemish disease that reduces tuber quality. The disease does not appear to significantly affect plant growth and yield, except when large numbers of galls are produced on roots. Diseased tubers are prone to secondary rots in the ground or in storage.

Consignments of potatoes grown for seed, fresh market and processing can be downgraded in value when affected by powdery scab. Severely affected crops may not be harvested at all or worst affected tubers may be discarded and the remainder marketed. Sorting diseased from unaffected tubers is labour intensive and reduces financial returns. Consignments of processing potatoes with an unacceptably high proportion of scabby tubers may be 'docked' at the factory gate resulting in a lower than contract price. The disease is of particular concern in the high value seed and washed, fresh potato markets in which there is a demand for negligible levels of scab.

Powdery scab is widespread throughout the traditional potato growing areas of Australia having reached epidemic proportions in many districts in the late 1970's. The pathogen, probably a native of Andes region in South America, was undoubtedly introduced into Australia in shipments of contaminated seed potatoes from Europe. Powdery scab has become increasingly important in other potato production areas of the world, including the USA where, until recently, the disease was considered insignificant. Research programs on various aspects of the biology and control of powdery scab are under way in Scotland, Switzerland, New Zealand and Australia. Although much is known about the pathogen and the disease, there are many gaps in our knowledge that need to be filled.

A good understanding of the life-cycle of the pathogen and the factors that influence disease help in determining control strategies.

Life-cycle of *Spongospora subterranea*

Spongospora subterranea is an obligate parasite requiring a living host to complete its life-cycle. There are two different phases in the life-cycle of this pathogen, one a multiplication process in root hairs in which inoculum is increased during crop growth, and the other in which resting or 'over-wintering' spores are produced in root galls and in pustules on tubers.

The fungus survives in soil as dormant cystosori (spore balls), which are aggregates of individual cysts (resting spores). These spores are resistant to adverse conditions, can survive the passage through the gut of farm animals, and probably remain viable for several years. In an experiment on survival, viable spores were detected in batches of spore balls that had been buried in a fallow soil for 4 years (R.F. de Boer, unpublished data). Under favourable conditions, and only in the presence of water, individual cysts germinate to produce a single swimming spore, the zoospore. It is likely that not all cysts or cystosori germinate at once but that, over time, there is either a staggered germination of cysts in individual cystosori or a staggered germination of cystosori scattered through the soil. Little is know about this process or the factors that govern dormancy and zoospore release.

On germination, primary zoospores released from cysts swim to a nearby root and infect the root hairs. A process of multiplication results in the development of zoosporangia, each zoosporangium containing up to eight secondary zoospores. These zoospores can re-infect roots so that progressively more zoospores are produced and inoculum (numbers of infective spores) levels increase (Kole and Gielink 1963). Potentially, several such cycles of infection and multiplication, each taking about 10

to 21 days, could occur if conditions are favourable during the life of the crop. As a consequence, potentially severe disease can result from relatively low soil inoculum. Little is known about the survival of zoospores. In comparison with cystosori they are probably short lived.

In another phase of the life-cycle, primary or secondary zoospores (from cystosori and zoosporangia, respectively) infect the cortical cells of roots or the developing (unsuberised) lenticels on initiating tubers. As the fungus undergoes multiplication, the cells of the root or tubers divide and enlarge resulting in the formation of pustules (scabs) on the tuber skin or galls on the roots, both containing masses of cystosori. Galls can be produced on the roots of young potato plants before tuber initiation (R.F. de Boer, unpublished observation).

Factors affecting disease

There are several factors relating to the pathogen, the crop and environment, that affect disease, including soil temperature, moisture, pH and structure, irrigation, rainfall, cultivar and the stage of tuber development.

Soil temperature, water and time of tuber set

Soil temperature and water are two of the most important factors affecting powdery scab. Scab on tubers is favoured by cool soil temperatures (10-20°C, optimum 12-15°C) and periods of saturation (after rain or irrigation) during early tuber initiation (Hughes 1981, Taylor and Flett 1981, de Boer *et al.* 1985, Taylor *et al.* 1986). A high soil water content encourages zoospore release. Soil in which most of the pore spaces are filled with water facilitates the movement of zoospores to the host.

Powdery scab on tubers results from infection by zoospores of proliferating or unsuberised lenticels (Hims 1976) which occur most frequently on newly initiated tubers or at the rose end (meristematic end) of older tubers. A population of tubers is most susceptible during the first 2-4 weeks after initiation (Hughes 1981, Taylor and Flett 1981, de Boer *et al.* 1985, Taylor *et al.* 1986, Diriwächter and Parbery 1991). After this time, most lenticels, apart from those developing at the rose end, are resistant to infection.

Roots are at risk from infection at any time providing conditions are favourable, although the pathogen appears to favour the youngest roots (R.F. de Boer, unpublished observation).

Because of the importance of temperature and water in disease development weather and season have a major influence on the development of powdery scab. Crops planted during the cool wet part of spring are more at risk than those planted later during warmer drier months. Similarly, where two crops in one year are possible, winter planted crops are more at risk than summer crops. Centre-pivot irrigation can greatly exacerbate the risk of scab in crops grown in warmer drier climates because of the high frequency of watering. Summer storms or irrigation with cold water can reduce soil temperatures to within the optimum range for powdery scab during hot summer days. Little is known, however, about the relative quantities and frequency of irrigation or rainfall that influence disease incidence and severity.

Cultivar resistance

Cultivars vary considerably in their relative susceptibility to powdery scab, although no cultivar is immune (Kirkham 1986, de Boer 1991). Kennebec is one of the most susceptible. As much as 95% of the surface of individual tubers can be covered with scab pustules when the disease is severe. Russet Burbank is one of the least susceptible with disease covering no more that 5% of the surface of individual tubers. There is no apparent relationship between the susceptibility tubers and roots to powdery scab (Hughes 1981). Significant numbers of galls can develop on the roots of Russet Burbank even though tubers of this cultivar are amongst the least susceptible (de Boer 1991).

The powdery scab problem in Australia is exacerbated by the fact that the majority of commercial cultivars grown today are highly susceptible to powdery scab.

Soil pH

Powdery scab is often said to be favoured by a high soil pH. However, in Australia the disease occurs in both acid and alkaline soils. There are many reports of trials demonstrating a clear relationship between changes in soil pH resulting from applications of either lime or sulphur and disease incidence and severity. Increasing the pH with lime has been shown to increase the incidence of tubers with powdery scab, whereas adding sulphur to soil had the opposite effect (e.g. Hughes 1981). However, there are as many reports demonstrating no effect of lime or sulphur on the disease.

This may not be a due to an indirect rather than a direct effect of pH on soil characteristics. Altering pH may change other factors that affect powdery scab or pH may interact with other factors that determine disease development. Wale *et al.* (1991) found a positive correlation between increasing soil pH and powdery scab but suggested that this may be related to the effect of pH on the solubility of Zinc in soil, a substance that is toxic to *S. subterranea*. There is anecdotal evidence from farmers that powdery scab is more severe in potatoes grown after improved pastures than after grass pasture, perhaps because of the application of lime to the former.

Soil structure

There is a higher risk of powdery scab in soils that have a relatively high water holding capacity or those that have poor structure because of impeded drainage. However, severe powdery scab can develop in crops grown in well drained sandy soils that are irrigated frequently.

Disease control

There is no single effective strategy for the control of powdery scab at present. Several strategies need to be adopted which, when combined can reduce the risk of the disease developing in a crop.

Cultivar susceptibility

The single most important strategy for minimising the risk of powdery scab is the use of less susceptible or resistant cultivars. This strategy plays only a minor role in controlling the disease at present as most cultivars are chosen on the basis of characteristics other than their susceptibility to powdery scab. The relatively immune processing cultivar Russet Burbank has largely replaced the highly susceptible Kennebec, by chance, ensuring the viability of potato production in the Central Highlands of Victoria, for example.

Little is known about the nature of resistance or immunity to powdery scab or the genes that control it. There is good evidence that resistance to powdery scab is inherited since there is significant correlation between resistance of progeny and the phenotype of parents in crosses with potatoes possessing different levels of susceptibility to powdery scab (Wastie 1991).

Chemical treatments

There are many fungicides with the potential to control both seed-borne and soil-borne powdery (Karling 1968, Harrison *et al.* 1997). The fungicides mancozeb and captofol were registered as treatments for the control of soil-borne powdery scab in Victoria and Western Australia in the 1980's (Carter *et al.* 1983, de Boer 1983) but registrations are no longer current. New, more effective fungicides have shown the potential to significantly reduce the incidence and severity of powdery scab and improve marketable yields when used as seed and soil treatments in trials in Australia, New Zealand and the United Kingdom (Braithwaite *et al.* 1994, Dixon and Graig 1994,Falloon *et al.* 1996). Improvements in the methods of application, ensuring that the fungicides are placed in the zone of developing tubers will further enhance efficacy.

Seed treatments and soil disinfestation (fumigation) and fungicides treatments do not eliminate powdery scab. Their efficacy may depend on the interaction between levels of soil inoculum, cultivar susceptibility and disease risk factors. The relatively high cost of some of these fungicides may limit their use to high value potato production. Nevertheless, chemical treatments can be an important component of integrated management strategies for powdery scab whilst resistant cultivars are in development.

Managing soil water - irrigation scheduling

The critical period of tuber susceptibility at early tuber set can be exploited in the control of powdery scab. In trials in Victoria, withholding irrigation during a 3 week period around early tuber set significantly reduced the incidence and severity of powdery scab on a susceptible cultivar in comparison with normal irrigation scheduling (Taylor and Flett 1981, Taylor *et al.* 1986). Where withholding water is impractical, reducing the amount and frequency of watering during this critical period may reduce the risk of severe disease in a crop. Further research is needed to determine usefulness of irrigation management in areas where crops require frequent watering.

Cultural practices

Hygiene
Good hygiene is critical in preventing the contamination of 'new' uninfested soil. Diseased tubers, dust in sheds or infested soil are sources of contamination of seed or equipment (de Boer 1983, Harrison *et al.* 1993). Seed tubers with no apparent symptoms of powdery scab may be contaminated with spore-balls of *S. subterranea* (de Boer *et al.* 1982, Harrison *et al.* 1993) and have as high a risk of spreading the disease to progeny as seed tubers with scab (R.F. de Boer, unpublished data).

Rotation
Long rotations (3-5 years) are recommended as a control measure for powdery scab (Wenzl 1975) but observations in Australia (R.F. de Boer, unpublished data) and elsewhere (Wale 1987) suggest that even 5-year rotations are not long enough. There is little published information on the effects of rotation on powdery scab. Short rotations can very quickly build-up high levels of soil inoculum in areas where conditions are very favourable for powdery scab (R.F. de Boer, unpublished data).

Soil structure
Maintaining good soil structure has implications for powdery scab management in soils that are prone to damage through frequent cropping and compaction by heavy machinery. Soils with poor structure are prone to water logging and, therefore, an increased risk of powdery scab.

Integrated management of powdery scab

Scottish researchers have devised a scheme that attempts to predict the severity of powdery scab that is likely to develop in a crop by assigning a value or score to the various 'risk' factors outlined above (Burgess and Wale 1994). They concluded that its accuracy as a disease prediction system is limited because it was impossible to predict, at the time of planting, temperature and rainfall at the critical stage of tuber susceptibility, or to quantify soil drainage.

A consideration of the various factors that affect the incidence and severity of powdery scab forms the basis of an integrated control as a strategy for managing powdery scab. Such a strategy would involve manipulating as may of these factors as possible and, although each one may not have a dramatic influence on the disease, combined they may significantly reduce the risk of severe powdery scab in a crop.

Project objectives

A number of issues regarding powdery scab concern growers at present. These include the effect of crop rotation on powdery scab and need for seed and soil chemical treatments for disease control. Anecdotal evidence from growers suggests some influence of rotation on the incidence and severity of powdery scab in crops. The objectives of this project were to

- evaluate common species of rotation crops as potential hosts of powdery scab, determine their role, if any, in the life-cycle of *S. subterranea* and establish whether any potential hosts contribute to the maintenance of inoculum of the pathogen and

- evaluate chemical treatments for the control of seed-borne and soil-borne powdery scab.

6.2 Studies on alternative hosts and on the influence of rotation on powdery scab

The powdery scab pathogen *S. subterranea* can infect the roots of many species of higher plants, including weeds, found on arable land in Europe (Würzer 1964, Janke 1965, Jones and Harrison 1969, 1972). In Australia, de Boer (unpublished data) also found that the pathogen could infect the roots of several species of plants grown in rotation with potatoes including representatives of legumes legumes, grasses and cereals.

All these studies were conducted under controlled conditions (high levels of inoculum, optimum soil temperature and moisture for infection) in greenhouses and infection resulted in the development of zoosporangial phase of the life-cycle. Würzer (1964) and Janke (1965) reported finding galls on the roots of several species of Solanaceae in their studies. Only Janke (1965) reported finding spore balls of *S. subterranea* in root galls and only then on *Nicotiana rustica* (Tobacco) and *Solanum nigrum* (Nightshade). Janke concluded, after three years of field tests under conditions favourable to powdery scab, that *S. nigrum* and *S. dulcamara* (two species of nightshade) were not important as hosts because galls did not develop on their root systems.

Little is known about the role of alternative hosts in the survival of *S. subterranea* in the intervening period between potato crops, particularly with regard to their contribution to inoculum in soil. There have been no systematic searches for the presence of the disease on the roots of species other than potato in the field. Although spore balls produced in root galls and in tuber pustules facilitate the long-term survival of the pathogen between potato crops, little is known about the longevity of zoospores produced in root hairs.

Long rotations (3-5 years) are recommended for the control of powdery scab (Wenzl 1975) although observations of disease severity in the field suggest that 5 years is not long enough (R.F. de Boer, unpublished data, Wale 1987). No systematic studies of the effects of rotation on powdery scab.

The objectives of this part of the project were to

- evaluate the relative susceptibility of different species rotated with potatoes to *S. subterranea* in controlled environments,
- develop a method of quantifying populations of the pathogen in soil,
- evaluate the effects of alternative hosts on levels of soil inoculum and
- evaluate the effects of rotation on powdery scab in field experiments.

6.2.1 Alternative hosts and their role in the life-cycle of *S. subterranea*

Summary

The seedlings of several different plant species, used in rotation with potatoes, were tested for their susceptibility to root infection by *S. subterranea*. Of 16 species tested, 11 became infected. The severity of infection (rated as the abundance of primary zoosporangia in roots hairs) was highest in the roots of the tomato controls ('Roma', 'UC 82B'), intermediate in canola and 'York Globe' fodder turnip and least in wheat, barley, turnip, 'Ranji' fodder rape, linseed, and perennial ryegrass ('Ellett', 'Nui'). The roots of oats, lucerne, subterranean clover, white clover and ryecorn were not infected. This contrasts with earlier studies in which the roots of white clover, subterranean clover, lucerne and oats were infected, as well as red clover, cluster clover, and cocksfoot (R.F. de Boer, unpublished data).

Root galls which contain the survival spores (spore balls or cystosori) were not found on roots of any of the species tested, although they have been reported to occur on the roots of several species from the Solanaceae under controlled glasshouse conditions elsewhere.

This study confirms that the roots of a wide range of plant species are susceptible to the primary stage of the life cycle of *S. subterranea* and that plants belonging to the Solanaceae family of plants are the most susceptible. We were unable to determine the role, if any, of these alternative hosts in maintaining the populations of *S. subterranea* in soil and further work is needed.

The stage of root infection found on alternative hosts in this study probably does not play a major role in the long-term survival of *S. subterranea*. Because only an intermediate stage of infection developed on these hosts, the fungus did not ccomplete its life-cycle by producing spore balls. Zoospores produced in zoosporangia are unlikely to survive in soil for prolonged periods, in contrast with cystosori, which can survive in soil for several years. Root galls containing cystosori (survival spores), another stage in the like-cycle of *S. subterranea*, have only rarely been found on the roots of species other than potatoes (nightshade and tomatoes).

Introduction

Experiments to evaluate the relative susceptibility of several species of plants commonly rotated with potatoes were conducted under controlled conditions in growthrooms and glasshouses. Tomato seedlings, rather than potato plants, were used as controls in these experiments because they were easily germinated and could be produced in large numbers when required.

Materials and Methods

Experiments on powdery scab have proven to be technically difficult in that specific conditions of temperature and soil moisture are required to obtain infection. An experiment to determine the relative susceptibilities of different plant species to infection by *S. subterranea* was repeated 3 times before infection of tomato tests plants was successful.

Spore ball (cystosori) inoculum
Pustules of powdery scab were scrapped from the surface of heavily diseased tubers. Bulked material was macerated in water with an electric blender, washed through as nest of sieves and the material remaining on the 53µm, 45µm and 38µm sieves was washed onto standard filter paper and allowed to air dry. Spore ball preparations were stored in opaque bottles at room temperature. Spores stored in this way can remain viable for several years. When required for experiments, the dried material was reconstituted by soaking on moist filter paper for several hours.

Host tests
Seed of several different plant species grown in rotation with potatoes (Table 1) were planted in a standard seed raising mix over a two week period, depending on the species and its relative germination time and growth rate. For convenience, tomato rather than potato was used as a control. Over a period of 5 to 14 days after first seed was planted seedlings were transferred to 140cm diameter black plastic pots containing a coarse sand, peat and coal dust (6:2:1) mix supplemented with slow release fertilisers, micro nutrients, iron and agricultural lime. Additional pots of tomatoes, to be used to monitor disease and disease progress were also planted. Seed of some species failed to germinate and were, therefore, not included in this study.

Six days after the last seedlings were transplanted, pots were inoculated with *S. subterranea* by adding a 100mL suspension of 6.6 x 10^4 cystosori that had been incubated at 10°C for 48hrs. Experiments by Merz (1989) showed that 'primming' cystosori in water at a cool temperature favoured infection.

Inoculated pots were immersed, up to the soil line, in water, incubated in a cool room at 15% for 48 hrs, drained and placed in a glasshouse with air temperatures maintained at 15°C-25°C

Experimental design was 5 plants/pot, with 4 replicate pots for each species. Pots were arranged on glasshouse benches in a randomised block design.

Twenty eight days after inoculation zoosporangia of *S. subterranea* were noted in the roots tomato test plants. 40 days after inoculation, seedlings were removed from soil, adhering soil washed from roots, and roots systems of each plant stored in Formol-Acetic-Alcohol (FAA) (13mL, 5mL, 200mL formalin, acetic and 50% ethyl alcohol, respectively) fixative.

Table 1 A list of different plant species tested for their susceptibility to root infection by *S. subterranea* in glasshouse experiments

Common name and variety	Scientific name
Tomato 'Roma' (Solanaceae)	*Lycopersicon esculentum*
Tomato 'UC 82B' (Solanaceae)	
Wheat 'Meering' (Poaceae)	*Triticum aestvum*
Barley 'Schooner' (Poaceae)	*Hordeum vulgare*
Oats 'Esk' (Poaceae)	*Avena sativa*
Ryecorn (Poaceae)	*Secale cereale*
Ryegrass 'Nui' (Poaceae)	*Lolium perenne*
Ryegrass 'Ellett' (Poaceae)	
Linola (Linseed) (Linaceae)	*Linum usitatissinum*
Subterranean Clover 'Larisa' (Fabaceae)	*Trifolium subterraneum*
Subterranean Clover 'Trikkala' (Fabaceae)	
White Clover 'New Zealand White'[A] (Fabaceae)	*Trifolium repens*
White Clover 'Haifi' (Fabaceae)	
Red Clover 'Cowgrass'[A] (Fabaceae)	*Trifolium pratense*
Red Clover 'Pawera'[A] (Fabaceae)	*Trifolium pratense*
Lucerne 'Pioneer L34 (Fabaceae)	*Medicago falcata Ssp sativa*
Fodder Rape ' Rangi' (Brassicaceae)	*Brassica napus Ssp olifera*
Fodder Rape 'Pasja' (Brassicaceae)	*Brassica campestris Ssp rapifera*
Fodder Rape 'York globe' (Brassicaceae)	*Brassica campestris Ssp rapifera*
Oilseed Rape (Canola) (Brassicaceae)	*Brassica napus Ssp olifera*

[A] Seed did not germinate and were, therefore, not included in the test

Disease assessment

Twenty four 20mm long segments of lateral roots were taken at random from each plant, stained with acid fuchsin in lactic acid and glycerol and examined for the presence of zoosporangia of *S. subterranea* at 100x magnification. The severity of infection, recorded as the abundance of zoosporangia in the roots hairs, was rated on a scale of 0-4 (after Flett 1983 and Merz 1989) where

0 = no sporangia,
1 = only a few sporangia (1-3 roots infected per microscopic field),
2 = several roots with sporangia (4-6 roots infected),
3 = sporangia regularly present, moderate infection (7-9 roots infected) and
4 = sporangia regularly present, heavy infection (>10 roots infected)

Results were analysed by Analysis of Variance to compare the relative abundance of zoosporangia in the roots of the different hosts.

The infectivity of zoospores from alternative hosts to tomato seedlings

An experiment was conducted to determine the infectivity of zoospores from alternative hosts. A tomato test system was established in which tomato plants were grown in a nutrient solution in growthroom with a day/night temperature regime of 20°C/15°C, inoculated with cystosori of *S. subterranea*, removed from the infected nutrient solution after two days and grown alongside a fresh tomato seedling. Zoosporangia failed to develop in the inoculated tomato seedling.

Results and Discussion

Zoosporangia of *S. subterranea* were detected in tomato test plants 35 days after inoculation. The severity of root infection varied (P<0.001) between the different plant species. *S. subterranea* was detected in the roots of 11 of the 16 species tested. Severity was the highest in the two tomato varieties tested, intermediate in the *Brassica* species canola and 'Pasja' turnip and lowest in wheat, barley, linola, perennial ryegrass ('Ellett' and 'Nui') and 'York Globe' turnip. Zoosporangia were two times more common (P<0.001) in the roots of tomato seedlings than in those of canola. Zoosporangia were not detected in the roots of subterranean clover, white clover, lucerne and ryecorn and oats. Galls containing cystosori of *S. subterranea* were not found on the roots of any species.

These results confirm the results of previous studies by de Boer (unpublished data) and others (Würzer 1965, Janke 1965, Jones and Harrison 1969, 1972) that *S. subterranea* can infect the roots of a wide range of plant species under controlled glasshouse conditions. In contrast to the results of this study, de Boer (unpublished data) recorded infection in the roots of subterranean clover, white clover, lucerne and oats, as well as red and cluster clover and cocksfoot. The reasons for this inconsistency are not known. Many of the conditions governing zoospore release from spore balls, and infection, are not known. Plant or root age may influence infection. Young healthy roots appears appear to be more susceptible than older roots. Difficulties in obtaining consistent release of zoospores from spore balls has been reported (Harrison *et al.* 1997) and this may be influenced by conditions in which they are stored prior to use (Harrison *et al.* 1997, Merz 1989). This could partly explain problems in obtaining infection in the studies reported here, since the experiment were repeated three times before tomato controls became infected. The duration of the infection period at the time of inoculation, and the temperature at this time, may also have influenced infection.

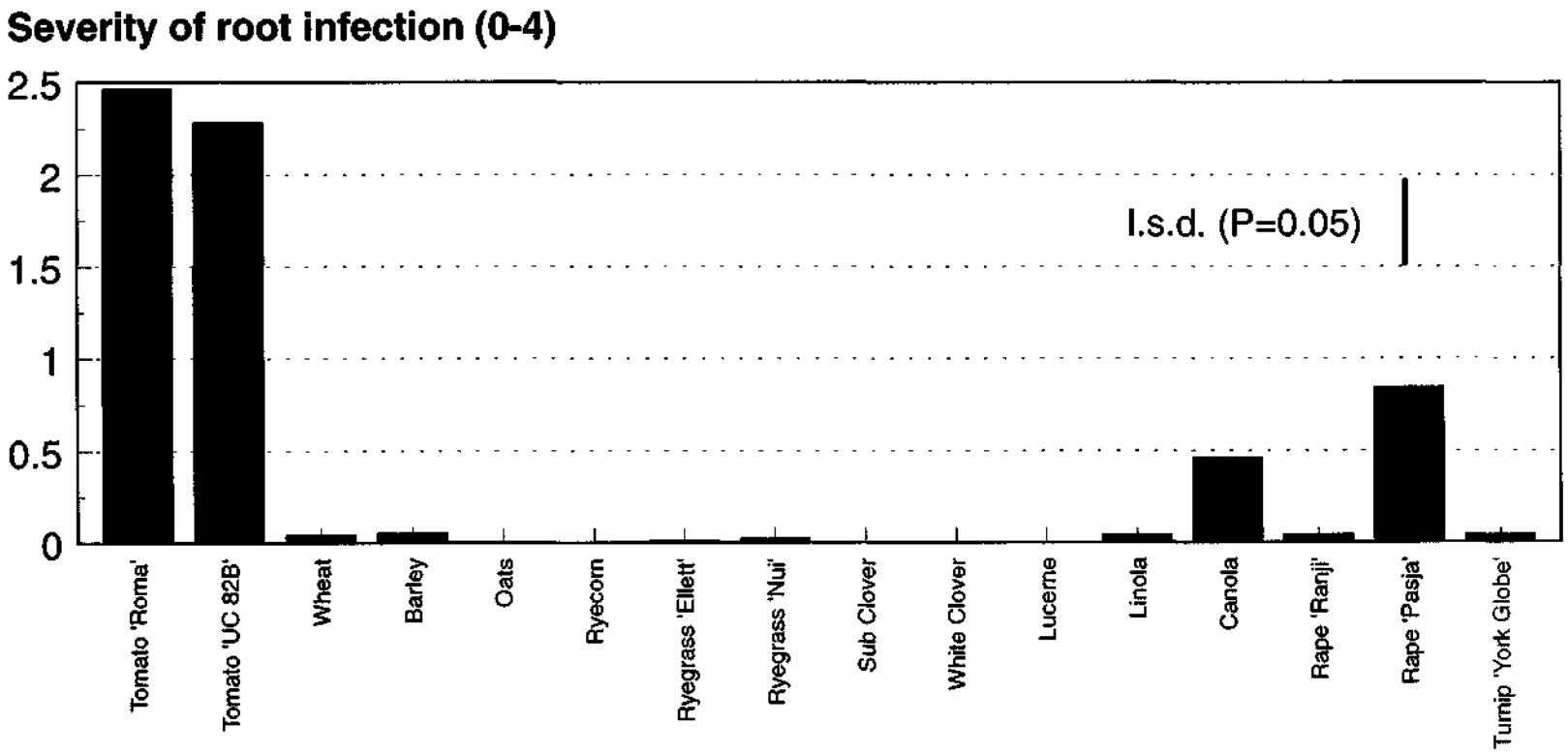
This study was not able to determine the role zoosporangial stage of infection of alternative hosts, if any, in maintaining populations of *S. subterranea* in soil in the life of this project. Zoospores of the fungus are unlikely to play a major role in the long-term survival of *S. subterranea,* although nothing is known about their survival in soil after release from the zoosporangia. In potatoes, the root hair infection cycle appears to play a role in the multiplication of spores before tuber initiation (Wale 1991). The fungus has not completed its life-cycle without the production of spore balls.

Galls have been reported to occur on the roots of several species of Solanaceae under controlled conditions in the glasshouse (Würzer 1965, Janke 1965), although they were not found on the same weeds in the fields after 3 years of trials (Janke 1965). However, zoosporangia and galls with spore balls were found on the roots of nightshade (*Solanum nigrum*) plants in a potato field in Tasmania (Hoong Pung, R.F. de Boer, unpublished data). Galls are also reported to occur on tomato rots in commercial glasshouses (Blancard 1992). Evidence to date suggests that root galls on these hosts only develop under exceptional circumstances of high levels of soil inoculum, a high pH after the regular application of lime and extended periods of soil moisture and temperature that are favourable for infection.

Trap (decoy) crops have been used to reduce populations of some pathogens. White (1954) in Australia and Winter and Winger (1983) in Switzerland have reported reduced levels of powdery scab in potatoes after growing a crop of *Datura stramonium*. The efficiency of a trap crop depends on the its ability to stimulate the germination of more resting spores than are produced in the plants that crop.

The studies reported here describe primary root infection (first cycle of zoosporangial production from infection by zoospores released from spore balls) in seedlings of alternative hosts under controlled conditions of temperature and moisture. Further research needs to determine whether soil inoculum levels used in experiments equate with natural levels in soil, to evaluate root infection of alternative hosts after several infection cycles to determine the potential of the fungus to produce galls and spore balls and complete the life-cycle on these hosts .

Fig. 1 The susceptibility of different plant species to root infection by *S. subterranea* in a glasshouse experiment (Severity = abundance of zoosporangia in roots)



6.2.2 Towards a method of quantifying populations of *S. subterranea* in soil

Summary

Soil was artificially inoculated with cystosori of *S. subterranea* to determine the relationship between different inoculum levels and the severity of infection of roots of tomato seedlings in a soil 'baiting' test. Zoosporangia of the fungus were present on roots of seedlings grown with the lowest level of inoculum tested (43 cystosori/100g soil). The severity of root infection peaked at 22 000 cystosori/100g soil but the test could not distinguish between that concentration and 44 000 cystosori/100g soil. This study provides the basis for developing a soil baiting test to determine the relative populations of powdery scab in soils using the Most Probable Number technique.

Introduction

An important tool in studying the effects of rotations on a pathogen is to be able readily detect it in soil and to quantify its population. At present, the most practical method of testing for the presence of *S. subterranea* is by 'bioassay' or 'bait-test' (Kole 1954, Flett 1983, Wale *et al.* 1993). Tomato seedlings are grown in samples of infested soil under conditions conducive to root infection and the abundance of zoosporangia in root hairs assessed after 3 weeks to determine the severity of infection. The upper and lower limits of detection of inoculum are narrow and such a test will not be able to detect very low numbers of cysts or distinguish between the high number of cysts.

Researchers in the Netherlands has successfully developed a test to quantify populations of *Polymyxae betae* in soil using a Most-Probable-Number (MPN) method. The organism, an obligate parasite of sugar beet roots and belongs to the same family as *S. subterranea.* The MPN technique involves diluting soil samples with sterile sand in a prescribed dilution series, baiting each diluted sample with tests plants and assessing the severity of infection at the last level of the dilution series in which the organism was detected. Results are then analysed using standard MPN programs to calculate the 'most probable' pathogen population. This allows comparisons of populations in soils relative to one another.

The aim of this part of the project was to study the relationship between inoculum levels and infection of tomato seedlings and to develop a MPN test for *S. subterranea.* This test could be used to measure populations of the fungus to evaluate the effects of alternative hosts on the population of spores in soil.

Materials and Methods

Tomato seed 'Roma', germinated in seedling trays, were transplanted into 100mm diameter black plastic pots (3 plants/pot) containing the sand/peat/coal potting media (400g/pot) described in section 6.3.2. Pots were kept in a growthroom maintained at 20°C day/15°C night. After 7 days, pots were inoculated with suspensions of cystosori (prepared as in 6.3.2) at 10 different concentrations, including an uninoculated control. Suspensions had been incubated at 15°C to 'prime' the previously dry cystosori. Concentrations of 0, 2, 5, 10, 25, 50, 100, 300, 500, 1000, or 2000 cystosori/mL were added to pots at equivalent rates of 43, 213, 531, 1.1×10^3, 2.2×10^3, 6.4×10^3, 1.1×10^4, 2.2×10^4 or 4.3×10^4/100g soil. After inoculation, soil in pots was flooded for 5 days by placing each pot in a container and adding water to the soil line to facilitate infection of roots by *S. subterranea.*

The experiment was a randomised block design replicated 3 times with 3 plants in each pot. After 21 days plants were removed from pots, roots washed in a stream of water to remove adhering peat, and each root system stored in FAA. The abundance of zoosporangia on roots was assessed on 12, 20mm segments of lateral roots taken at random from each of the 3 plants from each of the 3 replicate concentrations. Roots pieces were stained with acid fuchsin (Section 6.2.1), the number of zoosporangia on each length of root were counted and the mean number for each of 3 plants per replicate concentration recorded.

Results and Discussion

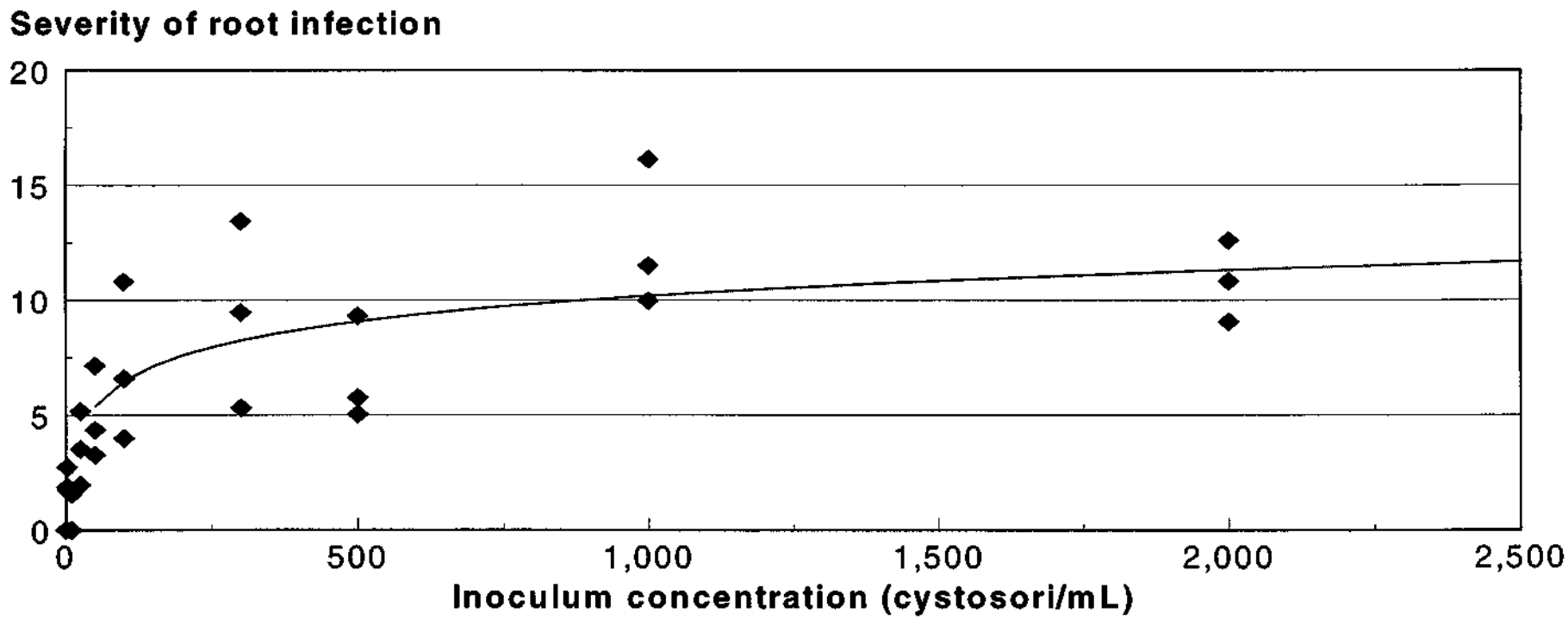
Root systems were successfully infected by *S. subterranea* at the lowest concentration of spores (43 cystosori/100g soil) (Fig. 2). Severity peaked at concentrations of 10^3 and $2x10^3$ cystosori/mL (2.12 and $4.24x10^4$/100g soil) but was no greater at the highest concentration. The test could not distinguish between the two highest concentrations illustrating the limitations of a simple baiting test in quantifying spore populations in soil. A soil dilution end-point method, such as in the Most-Probable-Number technique, aims to dilute soil so that populations are within the range that can be quantified within the limits of the tomato bait test.

Detection of 3-10 cystosori (per g of soil) with tomato baits have been reported (Merz 1993, Wale *et al* 1993). It has been suggested that the quantification of very high inoculum levels would require the testing of very small amounts of soil (Harrison *et al.* 1997). However, a soil dilution method would achieve the same aim with greater precision.

Further work is needed to develop this test. Comparisons between severity of infection on roots grown in naturally infected soil and artificially infected soils will give an indication of natural soil populations. The test will be a useful research tool and could potentially be used for decision making on farms.

Other methods of detecting *S. subterranea* in soil, on tubers or in roots are being developed. These include ELIZA systems based on polyclonal antiserum (Harrison *et al.* 1993) or monoclonal antibodies (Wallace *et al.*1995) or using nucleic acid based detection systems (Polymerase Chain Reaction) (Mustasa *et al.* 1993, J.W. Marshall and S Bulman, NZ, personal communication). These methods are potentially very sensitive but need considerable development before they can satisfactorily detect spore balls *in-situ*.

Fig. 2 The relationship between the inoculum concentration of *S. subterranea* and the severity of infection of tomato roots in a glasshouse experiment. (Severity = mean no. zoosporangia/20mm length of root)



6.2.3 The effects of rotation on powdery scab

Summary

Two trials were conducted on a volcanic loam at Clarkes Hill, in Victoria, to evaluate the effects of crops preceding potatoes on powdery scab. The crops included mixed pastures (grasses and clovers), pastures in which covers were sprayed with selective herbicides over an 18 month period prior to potatoes, and different cycles of green manure, fodder rape or forage cereals between the pasture phase and potatoes (ryecorn/sudax/ryecorn or ryecorn/fodder rape/ryecorn).

The incidence and severity of powdery scab was no different in potatoes (cvs Kennebec or Toolangi Delight) after grass pasture or after the different ryecorn or fodder crop combinations than in potatoes after a conventional pasture. These preliminary trials suggest that the crop preceding potatoes may not have a significant influence on powdery scab in the potato crop. Rotations could affect powdery scab over the long-term if they change soil physical and chemical conditions such as soil structure and pH. Powdery scab is favoured by poor soil drainage and by relatively high pH.

Introduction

Potatoes are often grown after pastures of 2 or more years duration. One or more crops (cereals, fodder rapes or cereals, green manure crop) follow potatoes before pastures are sown down again. There is very little information on the effects of rotation on powdery scab of potatoes, especially in the context of Australian potato production. Although rotations of three to five years are often recommended for the control of powdery scab . However, a high incidence of the disease is common in potatoes grown after several years of pasture.

Anecdotal evidence from growers suggests that the incidence and severity of powdery scab is greater in potatoes grown after an improved pasture (mixture of clovers and grasses) than after a grass pasture. This suggests that spraying grasses from improved pastures or other crops prior to potatoes may influence the levels of powdery scab.

Two trials were conducted on a growers property to examine the effect of different cropping sequences on powdery scab in potatoes.

Materials and Methods

Two trials were conducted on a property at Clarkes Hill near Ballarat in Victoria. Paddocks on this farm have a history of powdery scab. Soil type is a volcanic loam (kraznozem). Five-year rotations are normal practice (potatoes one in every four years).

Details of the trials and rotation treatments are described in Table 2.

Trial 1

The first trial was established by the grower before the start of this project. Four different treatments were established by dividing a paddock into roughly equal segments (main plots) parallel to the longest boundary but with each segment perpendicular to a gentle gradient in paddock. Rotation 1 occupied the highest part of the paddock, followed by 2, 3 and 4 (lowest) (Table 2) . A commercial crop of Russet Burbank was planted across the four rotation treatments in November 1993. As Russet Burbank is relatively tolerant to powdery scab, four replicate double row plots (subplots), each 2m long, of the susceptible cv. Toolangi Delight, were planted amongst the Russet Burbank crop (Russet Burbank tubers were removed and replaced with Toolangi Delight) in each rotation treatment (total of 16 plots). All tubers were harvested from subplots in July 1994, washed to remove adhering soil and the severity of powdery scab on each of 50 tubers recorded by assigning tubers to one of 13 categories of 0, <1, 2-5, 6-10, 11-20, 21-30, 31-40, 41-50, 51-60, 61-70, 71-80, 81-90 or 91-100% of tuber surface affected and the average for each 50 tubers calculated.

Table 2 Details of two rotation trials, Clarkes Hill, 1993/94 and 1994/95 (5-yr rotation, potatoes 1 in 4)

(Trial 1, 1993/94 - potatoes (cv. Toolangi Delight) sown in November '93 and harvested in July '94; Trial 2, 1994/95 - potatoes (cv. Kennebec) sown in November '94 and harvested in September '95)

Rotations		Treatments
Trial 1, potatoes 1993/94		
1.	Pasture (3 years)	Clover dominant pasture ('NZ White' clover, 'Tamar' white clover, 'Cowgrass' red clover) with perennial ryegrass (Vicrye), cultivated in Aug. '93
2.	Pasture Grass	Pasture sprayed with clover selective herbicides (Ester 80, Dicamba) in Feb.' 92, Aug. '92, Feb. '93, cultivated in Aug. '93
3.	Pasture - Ryecorn (*Secale cereale*) - Sudax (*Sorgham* grass) - Ryecorn	 Sown March '92, ploughed-in Sept. '92. Sown in Oct. '92, ploughed-in Feb. '93 '93
4.	Pasture - Ryecorn - Fodder rape (*Brassica napus biennis)* 'Ranji' - Ryecorn	 Sown March '92, ploughed-in Oct. '92 Sown in Nov. '92, ploughed-in March '93 Sown in March '93, ploughed-in Aug. '93
Trial 2, potatoes 1994/95		
1.	Pasture (3 years)	Grass dominant, perennial ryegrass (Vicrye) and clovers ('NZ white' clover, 'Tamar' white clover, 'Cowgrass' red clover), cultivated in Aug. '94
2.	Pasture Grass	Pasture sprayed with clover selective herbicides (Ester 80, Dicamba) in Feb.' 93, Aug. '93, Feb. '94, cultivated in Aug. '94
3.	Pasture - Ryecorn - Fodder rape - Ryecorn	 Sown Feb. '93, ploughed-in Sept. '93 Sown in Nov. '93, mulched & ploughed-in Feb '93 Sown in March '93, mulched & ploughed-in Aug. '93

Trial 2

This trial was established on a paddock adjacent to Trial 2 in the following year. The paddock was divided into 9 segments (main plots), each perpendicular to the gradient, with 3 rotations replicated 3 times and randomised down the gradient. A commercial crop was planted across the rotation treatments (with the gradient) in November 1994. Four subplots of cv. Kennebec, each 7.5m long with 25 tubers, were established across each replicate rotation treatment (36 plots in total). Crop management was as for a commercial Russet Burbank crop. All tubers were harvested from subplots in July 95, washed to removed adhering soil and the severity of powdery scab, silver scurf and black dot on the surface of each of 50 tubers recorded. Powdery scab was assessed as in Trial 1. The severity of silver scurf and black dot was assessed on a scale of 0 to 3 (0, no disease; 1, <5%; 2, 6-30%; 3, >30% of tuber surface affected). Results were analysed by Analysis of Variance.**Results**

Trial 1, 1993/94

The incidence of powdery scab in Toolangi Delight varied between 17% and 40% of potatoes affected (Table 3). Severity was generally very low, with a average of less than 1% of the tuber surface covered with scab pustules in each treatment. Neither the incidence nor severity of powdery scab differed significantly between treatments.

Trial 2, 1994/95

Kennebec tubers had a high incidence of powdery scab, silver scurf and black dot. The severity of powdery scab averaged from 9% to 20% of the tuber surface covered with pustules (Table 4). Although there were some minor ($P<0.1$) differences in the incidence and severity of powdery scab between treatments, there was no pattern relating disease levels to rotation. There was no apparent effect of rotation treatments on the incidence and severity of silver scurf and black dot.

Discussion

Although these studies are only preliminary, they suggest that crops sown before potatoes may not have a significant effect on the incidence and severity of powdery scab in the potato crop. There are no other reports on the effect of rotation on powdery scab.

Because of the apparent ability of *S. subterranea* to multiply in the roots hairs prior to tuber set (Harrison *et al.* 1991), there may be little relationship between initial soil inoculum levels and the incidence and severity of powdery scab in a crop. High levels of disease may result from relatively low levels of soil inoculum. This process may mask any possible effect of rotation crops on soil inoculum when disease incidence and severity in the potato crop rather than soil inoculum are measured.

The trials were conducted in fields that had a history of powdery scab. Although Russet Burbank has been the main cultivar grown on the farm for several years, the high incidence of powdery scab on the susceptible cultivars used in trials suggests that inoculum of *S. subterranea* was not reduced significantly in the 1 in 4 rotation practiced on the farm. There are a number of possible explanations for this. Spore balls can remain viable in soil for at least 4 years (R.F. de Boer, unpublished data) and probably longer. Although tubers of Russet Burbank are relatively immune to powdery scab, prolific numbers of galls are produced on the root system (de Boer 1991), thereby maintaining soil inoculum. The significant numbers of volunteer potato plants that remain at the end of the 5 year cycle undoubtedly contribute to soil inoculum. Some solanaceous weeds can potentially produce galls with spore balls under field conditions (Würzer 1965, Janke 1965). Galls with spore balls were found on the roots of *Solanum nigrum* plants in a potato field in Tasmania (Hoong Pung and R.F. de Boer unpublished data).

Rotations that affect soil structure and chemistry over the long-term could potentially affect the incidence and severity of powdery scab. Powdery scab is favoured by high soil pH. Long term pastures dominated by grasses, for example, tend to become acid, whereas improved pastures have a combination of grasses and forage legumes and a relatively high pH after treatment with agricultural lime. Anecdotal evidence from some farmers suggests that the adoption of pasture improvement practice on their farms has coincided with increases in the incidence of powdery scab.

Increasing the frequency of cropping can lead to smaller soil aggregates, reduced drainage and subsequently a greater risk of powdery scab. For example, in an study in the UK, the incidence of scab was found to be greater in soil cultivated with a 'Shakaerator' than with a paraplough (minimum tillage implement) or a tined implement (Mackie and Munro 1986). This was related to differences in moisture capacities and water potential of the soils cultivated with the different implements.

Although there is little evidence to indicate that crops grown prior to potatoes can reduce the incidence of powdery scab, rotation is an essential management strategy for this disease. Long rotations minimise the build-up of high populations of the pathogen in fields and the control of volunteer potatoes and Solanaceous weeds must be an integral part of this strategy.

Table 3 Incidence and severity of powdery scab on potato tubers (cv. Toolangi Delight) cropped in different rotations (Mean of 4 replicates) (Trial 1)

(PAS mixed pasture of clovers and perennial ryegrass; GRASS, clovers killed with selective herbicides; RYE, ryecorn; RAPE, fodder rape; SUDAX, Sorgham grass)

Cropping history before potatoes	Powdery scab	
	% tubers affected	Severity[A]
PAS	30 (17-35)[B]	0.7
PAS - GRASS[B]	43 (19-39)	0.5
PAS - RYE - SUDAX - RYE	41 (19-39)	0.9
PAS - RYE - RAPE - RYE	27 (17-20)	0.4
F-test P value	ns	ns

[A] Proportion of the tuber surface covered with powdery scab pustules
[B] Range of disease incidence in 4 replicates
ns not significant, P<0.1

Table 4 The incidence of tuber diseases in potatoes (cv. Kennebec) in different rotations (Trial 2)

(PAS mixed pasture of clovers and perennial ryegrass; GRASS, clovers removed with selective herbicides; RYE, ryecorn; RAPE, fodder rape)

Cropping history before potatoes	Powdery scab		Silver scurf		Black dot	
	% tubers affected	Severity[A]	% tubers affected	Severity[B]	% tubers affected	Severity[B]
PAS	77	9.0	98	2.4	74	1.6
PAS	91	19.4	92	2.2	83	1.8
PAS	94	11.5	100	2.7	87	1.9
PAS-GRASS	89	14.4	97	2.4	77	1.7
PAS-GRASS	96	20.4	98	2.5	84	2.0
PAS-GRASS	98	21.2	98	2.5	84	2.1
PAS -RYE-RAPE-RYE	93	14.4	97	2.2	84	1.8
PAS -RYE-RAPE-RYE	90	13.8	96	2.3	86	2.1
PAS -RYE-RAPE-RYE	92	15.6	99	2.3	82	2.0
F-test (P value)[C]	0.1	0.01	ns	ns	ns	ns
Mean[D]						
PAS	87	13.3	97	2.5	81	1.8
PAS-GRASS	94	18.6	97	2.5	82	1.9
PAS -RYE-RAPE-RYE	91	14.6	97	2.3	84	2.0
F-test (P value)	ns	0.05	ns	ns	ns	ns

[A] Proportion of tubers surface covered with powdery scab pustules
[B] Severity rated on a scale of 0-3: 0, no disease; 1, <5%; 2, 6-30%; 3, >30% of tuber surface covered
[C] Mean of 4 replicate subplots in each rotation treatment plot
[D] Mean of 3 replicate rotation plot and 4 replicate subplot combination
ns not significant, P<0.1

6.3 Chemical control of powdery scab

Trials over many years in many different countries have shown that the powdery scab fungus, *S. subterranea,* is potentially controlled by several different classes of chemicals. However, not many chemicals were found to be effective in providing economic control of soil-borne powdery scab in the field. The efficacy of soil applied chemicals depends on their placement in soil in relation to the target organism and initiating tubers, their mode of action, mobility in soil, rate of adsorption onto soil particles and rate of leaching,

In the early 1980's, mancozeb (Dithane®) and captofol (Difolatan®) were registered as a soil treatments for the control of soil-borne powdery scab in Western Australia and Victoria, respectively. In Trials, these chemicals reduced the incidence of scab and improved the marketable yields but were not often used commercially. A mixture of Aretan® (organic mercury) and Formalin® (formaldehyde) was registered in Victoria for many years as a dip treatment for seed potatoes to control a range of pathogens, including *S. subterranea*. There are no registered treatments for the control of powdery scab in Australia today.

There has been renewed interest in the chemical control of powdery scab by researchers in the United Kingdom, Australia and New Zealand where the disease is a particularly serious problem. Chemicals which reduce disease incidence and severity in field trials included Zinc compounds (Wale *et al.* 1991) and flusulfamide (Dixon and Craig 1994) in the United Kingdom, fluazinam in Australia (Crop Care Australia) and fluazinam, flusulfamide, mancozeb, dichlorophen-Na, sulfur and cyprodinil in New Zealand (Genet *et al.* 1996). The chemicals dichlorophen-Na, fluazinam, flusulfamide and mancozeb, applied to diseased seed and planted in clean soil, reduced the incidence of powdery scab in progeny tubers in trials in New Zealand (Braithwaite *et al.* 1994). In recent trials in the United Kingdom, flusulfamide and fluazinam have provided good control of soil-borne powdery scab (J.S. Wale, personal communication). A Fluazinam tuber spray treatment has recently been registered in New Zealand for the control of seed-borne powdery scab (R. E. Falloon, personal communication).

In trials in Australia by Crop Care (Australasia), fluazinam was sprayed onto the seed tuber and into the soil at planting. The arrangement of nozzles, one ahead of the furrow opening disks and two spraying onto seed and into the furrow between the opening and closing disks, resulted in a high proportion of the fungicide above the seed sett in the area where new tubers were initiated. The two sets of disks over each row inverted and mixed treated soil. The fluazinam treatments significantly reduced the incidence of powdery scab in some trials. Results were variable and the effectiveness of the treatments depended on the method of application and planting equipment used. Treatments applied on planters with disks were more effective than on those with tines because of better mixing of treated soil with disks.

Chemicals have not provided complete control of the disease but increases in marketable yields of up to 4 times that of untreated controls in trials with a very susceptible cultivar conducted by Crop Care Australia have been reported (P.A. Taylor, personal communication). Chemical control has a place as part of an overall management plan for powdery scab. However, the effectiveness of soil-applied treatments may depend on the susceptibility of the cultivar to powdery scab, the inoculum level in soil and soil type and climate. Studies in New Zealand suggest that fungicides may be more effective in improving marketable yields with relatively low inoculum (Genet *et al.* 1996).

Experiments were conducted to evaluate the effect of fumigation with metham sodium and the effect of seed and soil-applied fungicides on the incidence and severity of powdery scab of potatoes.

6.3.1 Evaluation of fumigation with metham sodium for the control of soil-borne powdery scab and other diseases of potatoes in a volcanic loam, Clarkes Hill, Victoria, 94/95

Summary

The effect or fumigation with metham sodium on soil-borne powdery scab and other diseases of potatoes was investigated in a field trial in a commercial crop grown in a volcanic loam at Clarkes Hill in the Central Highlands of Victoria. Metham® was injected into soil at a rate of 740L/ha (313L metham sodium/ha) at the end of October 1994. Russet Burbank, Coliban and Kennebec seed setts and Kennebec minitubers were planted one month later (end November 94). At harvest in June 95, an average of 20%, 63% and 93% of Russet Burbank progeny and an average of 80%, 75% and 42% Coliban, Kennebec and Kennebec minituber progeny were affected with powdery scab, silver scurf and black dot, respectively.

Fumigation had no effect on weed populations prior to planting potatoes. Disease incidence and severity were no less in tubers harvested from the fumigated plots than from the untreated plots, irrespective of cultivar. Fumigation did not significantly affect the total numbers of tubers and total yield of Russet Burbank, nor the numbers and yield of potatoes in the seed, processing and unmarketable categories.

This study suggests that fumigation with metham sodium is not an economic proposition for disease control in the Central Highlands where relatively high soil organic matter and clay content and coarse structure (tilth) can reduce the effectiveness of this treatment. Optimum conditions for the effective treatment with metham sodium include a seed bed of fine tilth, relatively low organic matter, soil temperature greater than 10°C, a relatively high soil moisture content and access to irrigation immediately after the chemical is applied.

Fumigation with metham sodium has been reported to reduce, but not eliminate, powdery scab on Coliban potatoes in a study at Virginia, South Australia. and in the USA.

Introduction

Fumigation with metham sodium is becoming common practice in intensive vegetable growing areas and on bulb and flower farms. Although not common in potato production, the practice is increasingly being used by growers who can get high returns for potatoes and other crops grown in rotation with potatoes (often vegetables). Metham sodium has not been evaluated extensively in Australian potato cropping but these is evidence from the United States and South Australia that the fumigant has some activity against powdery scab.

A trial was conducted in a commercial Russet Burbank crop on a growers property at Clarkes Hill (near Ballarat in the Central Highlands of Victoria) to evaluate the effect of fumigation with metham sodium on weeds, powdery scab and other soil-borne diseases of potatoes. The growers aim was to control stem canker caused by *Rhizoctonia solani* in a commercial Russet Burbank crop but this cultivar is one of the least susceptible to powdery scab. A trial design was conceived to examine the impact of fumigation on diseases in plots in the commercial crop as well as in subplots of cultivars that were susceptible to powdery scab.

Materials & Methods

A field (5ha) on a 5-year-rotation (potatoes 1 in 4 years) with a 3-year-old pasture (clovers and grasses) was cultivated in July 1994 in preparation for planting of a potato crop in November 94. Soil on this farm is a volcanic loam (kraznozem) with relatively high levels of clay. Paddocks have a history of powdery scab. An area 100 m wide by 200 m long was divided into 6 plots (3 untreated and 3 for fumigation), each approximately 7.5 m (20 potato rows) wide by 200m long. Experimental design was 6 treatments (3 untreated and 3 fumigated), replicated 3 times in a completely randomised design. The site was rotary hoed in mid October, fumigated on 31 October and irrigated the following day.

Metham®, applied by a commercial operator, was injected below the soil (20cm deep) at a rate of 740L/ha (313L metham sodium/ha).

Russet Burbank potatoes (cut setts of Russet Burbank Certified seed dusted with Douglas Fir Bark) were planted on 26 November with a 2-row cup planter, 30cm apart in rows 80cm apart, along the 200m length of each plot. Seed potatoes had a moderate incidence and severity of silver scurf and a relatively high incidence and severity of black dot.

As Russet Burbank is relatively low in susceptibility to powdery scab, tubers of the susceptible cultivars Coliban and Kennebec were planted in small subplots within the main plots. Cut setts of Coliban and Kennebec and Kennebec minitubers were hand planted 20cm apart on 29 November in the centre of each plot, each variety in one of 3 adjacent 7.5m lengths of row after the machine planted Russet Burbank setts had been removed. Coliban tubers, which had a relatively high level of silver scurf, were dipped for 2 minutes in a thiabendazole solution before cutting. Coliban and Kennebec setts were dusted with Douglas Fir Bark after cutting.

The crop was managed (post planting weed control, irrigation and pesticides) by the grower in accordance with commercial practice for Russet Burbank.

Russet Burbank tubers were harvested by hand from 10, 1m lengths of row per plot on the 22 and 23 June 1995. Each 1m length of row was harvested from one of the centre 10 rows of each plot (at random) in every 20m length of plot. The entire length of each Coliban Kennebec and Kennebec minituber plots were harvested by hand.

Yield from Russet Burbank was determined by weighing and counting tubers in each of the 4 different size categories 35-100g, 100-350g, >350g and misshapen. A subsample of 50 tubers of each cultivar harvested from each plot and subplot were washed and assessed for the incidence (5 tubers affected) and severity of tuber skin diseases. The severity of tuber surface with powdery scab pustules was assessed by assigning tubers to different categories (0, 0-1, 2-5, 6-10, 11-20, 21-30 etc, of surface area covered) and calculating the average severity. The severity of symptoms of silver scurf and black dot were rated on a scale of 0-3 where ratings of 0, 1, 2 and 3 were no disease, <5%, 6-30% and >30% of tuber surface covered. Data was analysed by Analysis of Variance.

Results

In observations of weed emergence prior to planting, weeds were no less abundant in fumigated plots than in untreated plots. Symptoms of damage caused by *Rhizoctonia solani* (patches of stunted plants and stem canker and malformed plants at the time of senescence) were negligible throughout the life of the crop.

Powdery scab, silver scurf and black dot were found on tubers of all cultivars (Table 5 and 6). An average of 20% of Russet Burbank tubers were affected with powdery scab, compared with an average of 80% of tubers of Coliban and Kennebec. The incidence and severity of silver scurf and black dot were relatively high on all cultivars. The incidence of tubers with black scurf was negligible for all cultivars.

Fumigation had no significant effect on incidence and severity of powdery scab, silver scurf or black dot (Tables 5 and 6). The incidence of silver scurf tended to be less ($P<0.06$) in Russet Burbank tubers grown in fumigated compared with untreated soil. Numbers of tubers and yields in each size category, and the total number and yield of Russet Burbank in fumigated plots, did not differ significantly to those in untreated plots (Table 7).

Discussion

Fumigation of soil with metham sodium did have any tangible benefits in terms of yield and tuber quality for the grower on this commercial property in the Central Highlands of Victoria. Although relatively high levels of powdery scab, silver scurf and black dot developed in this trial, the incidence and severity of these diseases was no different in fumigated compared with untreated plots.

Weed control is a good indicator of the effectiveness of fumigation. The lack of weed control with fumigation in this trial suggests that the chemical was not effect in this instance. Metham sodium becomes volatile in contact with water but the chemical can be absorbed by organic matter and clay particules, thereby reducing its availability. Rate of volatilisation, movement through the soil profile and escape into the atmosphere depend on soil temperature and moisture.

Soil type and farming practice may account for the ineffectiveness of fumigation at Clarkes Hill. The paddock had been in pasture for up to three years. After cultivation to break up the pasture, soil had a coarse tilth (relatively large aggregates) and a high organic matter content, which included the crowns of grasses and clovers. Although this is considered to an ideal potato seed-bed, it is not ideal for fumigation. Optimum conditions for fumigation with metham sodium includes a seed bed of fine tilth (small soil aggregates, preferably sandy soils), such as that achieved by rotary hoeing, relatively low in organic matter, a soil temperature above 10°C, adequate moisture and access to irrigation immediately after fumigation. These conditions are difficult to achieve in this part of Victoria. Rotary hoeing would be necessary and this practice destroys soil structure.

The progeny of Kennebec minitubers developed relatively high levels of silver scurf, black dot and powdery scab. As minitubers are produced in an essentially disease-free environment, soil-borne inoculum was the most likely source for infection of progeny tubers by the three pathogens involved, highlighting the importance of role of soil-borne inoculum in disease development in traditional potato production areas. However, the Russet Burbank, Coliban and Kennebec seed planted in this trial carried inoculum of *H. solani*, and *C. coccodes* and probably traces of *R. solani* and *S. subterranea*. Had fumigation been effective in reducing soil-borne inoculum, the pathogens would have been introduced back into soil on the diseased seed potatoes.

Fumigation with metham sodium has been reported to reduce the incidence and severity of powdery scab in a trial at Virginia in South Australia (Trevor Wicks, SARDI, personal communication) and when applied through sprinkler irrigation systems in California, USA (Weinhold 1994). The effectiveness of the treatment depended on the susceptibility of the cultivar and the level of *S. subterranea* in the soil. A higher rate was recommended in fields with a high level of infestation by the fungus than in fields with a low level of infestation (Weinhold 1994).

Soil fumigation is practiced in many potato cropping areas around the world. Fumigants such as metham sodium are being used as replacements for the standard methyl bromide. Fumigation must be used together with 'clean' seed potatoes to be effective. However, there some evidence that the frequent use of fumigation is not sustainable (Lamers 1998) where comparisons have been made between fumigation and rotation.

Table 5 Effect of soil fumigation with metham sodium on the incidence and severity of powdery scab, silver scurf and black dot of potatoes in a field trial at Clarkes Hill, Victoria 1994/95

Treatment	Cultivar	Powdery scab		Silver scurf		Black dot	
		% tubers affected	Severity[A]	% tubers affected	Severity[B]	% tubers affected	Severity[B]
Untreated control							
Plot 1	Russet Burbank	40	0.3	87	1.0	97	1.9
	Coliban	71	5.4	61	0.9	35	0.6
	Kennebec	79	15.8	65	1.1	6	0.1
	Kennebec Minituber[C]	74	14.9	97	2.1	63	1.6
Plot 2	Russet Burbank	16	0.2	86	1.5	96	1.9
	Coliban	mv	mv	mv	mv	mv	mv
	Kennebec	mv	mv	mv	mv	mv	mv
	Kennebec Minituber	mv	mv	mv	mv	mv	mv
Plot 3	Russet Burbank	6	0.1	78	1.4	87	1.6
	Coliban	72	8.9	995	2.6	23	0.2
	Kennebec	77	10.4	98	2.8	30	0.4
	Kennebec Minituber	90	6.7	98	2.8	26	0.3
Fumigated							
Plot 1	Russet Burbank	30	0.3	30	0.4	92	1.8
	Coliban	89	15.8	73	1.3	82	1.9
	Kennebec	84	26.8	37	0.6	55	1.3
	Kennebec Minituber	mv	mv	mv	mv	mv	mv
Plot 2	Russet Burbank	34	0.6	27	0.4	95	2.1
	Coliban	88	16.0	79	1.4	66	1.5
	Kennebec	94	33.2	32	0.4	34	0.7
	Kennebec Minituber	92	27.7	65	1.08	51	1.0
Plot 3	Russet Burbank	6	0.02	74	1.3	92	1.8
	Coliban	48	2.0	69	1.3	35	0.7
	Kennebec	81	7.6	85	2.1	51	1.0
	Kennebec Minituber						

[A] Average proportion of tuber surface covered with powdery scab pustules
[B] Severity rating scab 0-3: 0 no disease; 1, <5%; 2, 3-30%; 3, >30% of tuber surface affected
[C] Grown from tissue cultured plantlets
mv Missing value - plots were destroyed by the wheels of a travelling irrigator.

Table 6 Effect of soil fumigation with metham sodium on the incidence and severity of powdery scab, silver scurf and black dot of potatoes in a field trial at Clarkes Hill, Victoria, 1994/95

(Averages of replicated plots)

Treatment/Cultivar	Powdery scab		Silver scurf		Black dot	
	% tubers affected	Severity[A]	% tubers affected	Severity[B]	% tubers affected	Severity[B]
Russet Burbank (Main plots)						
Untreated control	21	0.2	84	1.3	93	1.8
Fumigated	23	0.3	44	0.7	93	1.9
F-test (P=0.1)	ns	ns	0.06	ns	ns	ns
Mean of Kennebec & Coliban (Subplots)[C]						
Untreated Control	77	10.4	86	2.1	30	0.6
Fumigated	82	17.4	65	1.3	54	1.1
F-test (P=0.1)	ns	ns	ns	ns	0.1	ns

[A] Average proportion of tuber surface covered with powdery scab pustules
[B] Severity rating scab 0-3: 0 no disease; 1, <5%; 2, 3-30%; 3, >30% of tuber surface affected
[C] Averages values for Coliban, Kennebec and Kennebec minitubers are presented as there were no statistically significant differences between cultivars.
ns F-test not significant at P<0.1

Table 7 Effect of soil fumigation with metham sodium on the yield and numbers of tubers of Russet Burbank in a field trial at Clarkes Hill, Victoria 1994/95

(Numbers and yield of tubers per 10m length of row)

Treatments	Tuber size category										
	35-100g		100-350g		>350g		Misshapen		Total		Mean weight/tuber (g)
	No. tubers	Yield (kg)	No. tubers	Yield (kg)	No. tubers	Yield (kg)	No. tubers	Yield (kg)	No. tubers	Yield (kg)	
Untreated control	63.3	4.23	151.0	36.8	22.7	10.8	5.7	1.73	243	53.5	261
Fumigated	52.0	3.60	185.0	39.0	16.3	7.7	4.3	1.70	258	52.1	211
F-test (P=0.1)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns F-test not significant at P<0.1

6.3.2 Evaluation of chemical treatments for the control of soil-borne powdery scab (Spongospora subterranea) of fresh market potatoes in a field trial at Torquay Victoria, 1995/96

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(A report to Crop Care Australia)

Summary

Different chemical treatments, including flusulfamide, fluazinam, mancozeb, zinc oxide, ICIA5504 and potassium phosphonate, were evaluated for their efficacy against soil-borne powdery scab of potatoes in a field trial near Torquay, Victoria, in 1995. Potatoes produced in this area are predominantly for the fresh, brushed and washed markets. The trial was established on a sandy soil with a shallow clay base on a site with a history of severe powdery scab.

Soil treatments were sprayed onto the surface of raised beds (two rows wide) and soil rotary hoed before planting the cultivars Sequoia (highly susceptible to powdery scab) and Snowgem (low susceptibility) in mid June 1996. Plants emerged at between 6-8 weeks after planting. Tubers were harvested in January 1996 and assessed for the incidence and severity of powdery scab, common scab (*Streptomyces scabies*), black scurf (*Rhizoctonia solani*), black dot (*Colletotrichum coccodes*) and silver scurf (*Helminthosporium solani*). The number of tubers and yield were also recorded.

Symptoms of powdery scab and common scab occurred more frequently on Sequoia tubers (40% & 79% tubers affected, respectively) than on Snowgem tubers (18% & 45% tubers affected, respectively). The incidence and severity of diseases and number and yield of tubers of either cultivar were not significantly affected by chemical treatments when compared with the untreated control. However, some consistent trends were apparent in the data. On average, applications of fluazinam tended to result in less tubers with powdery scab (34% tubers affected), greater numbers and yield of tubers and a higher proportion of marketable tubers (≤5% of tuber surface with scab) of the susceptible cultivar Sequoia than in the untreated control (49% tubers with powdery scab). An application of ICIA5504 tended to reduce the incidence and severity of black scurf (2% of tubers affected) on Snowgem and the incidence and severity of black dot (37% tubers affected) on Sequoia in comparison with the untreated control (17% & 69% tubers affected, respectively).

The fungicide potassium phosphonate has been sold to farmers as a cure for several potato diseases. Regular foliar applications of this fungicide did not reduce the incidence and severity of powdery scab, common scab, silver scurf, black dot or black scurf.

These results indicate the potential for fluazinam to reduce the incidence of powdery scab on susceptible cultivars and for ICIA5504 to reduce the incidence of black scurf and black dot. The lack of control with the treatments in this trial may have been due to the method of application (sprayed over the entire plot surface rather than banding in the furrow) resulting in less than optimum rates, and possible leaching of chemicals during a long interval between planting and emergence (8-12 weeks).

Introduction

Powdery scab, caused by the fungus *Spongospora subterranea*, is one of the major diseases of potatoes in Australia. The diseases affects the quality of potato tubers and threatens the viability of the seed and washed ware potato industries, in particular, because of the negligible tolerance for scab on these commodities.

The disease can develop in a crop as a result of either planting infected seed potatoes or from soil-borne inoculum. The fungus survives in soil as cystosori (spore balls). The disease is favoured by

periods of cool (10-18 °C, optimum 12-15 °C) wet conditions (periods of saturation after rainfall or irrigation) during early tuber set when the tubers are susceptible to infection by zoospores.

There are very few options for controlling powdery scab. Although cultivars vary in susceptibility, most commercial cultivars grown today are very susceptible to scab. There are no registered chemical treatments in Australia for the control of either seed or soil-borne powdery scab. Research conducted in Europe, New Zealand and Australia have demonstrated the potential of several chemicals to control both seed and soil-borne powdery scab. Chemicals can potentially provide and important control option in integrated management strategies for this disease. The paper reports on the results of a field trial to evaluate the efficacy of several potential effective soil-applied chemical treatments for the control of soil-borne powdery scab and other diseases in a fresh market production area near Torquay in Victoria.

The results of a field trial comparing the effects of different soil-applied chemical treatments on the incidence and severity of powdery scab and other diseases on tubers of a highly susceptible and moderately susceptible cultivar are reported here.

Materials and Methods

Field Site

The trial site was situated near Torquay, approximately 10km south west of Geelong. Potatoes grown in this area (including the Bellarine Peninsula) are traditionally sold as brushed or washed fresh market potatoes. Soil type was a fine sand over clay (Northcote classification Dy 4.12) with a pH in the range of pH 5.3 to 5.9 in H_2O and 4.2 to 4.7 in $CaCl_2$. Potato crops in this area are normally planted in winter (May to June) and are not irrigated. The site was sown to potatoes (cv. Sequoia) in 1993/94 and the progeny of this crop severely affected with powdery scab. The entire crop, which was considered unmarketable, was left on the ground. During 1994/95 the site was covered with self-sown pasture and a high density of self-sown potatoes.

Table 8 Chemical treatments for the control of soil-borne powdery scab in a field trial, Torquay, Victoria 1995/96

Area/plot, 16m^2 (1.6mx10m, 2 plant rows wide); Total area of plots 0.192ha; Sprayed area/plot 13m^2 (1.3m wide strip); Soil fungicide treatments sprayed at the equivalent of 250L/ha H_2O.

Treatment no.	Fungicide	Fungicide rate/ha (kg)	Product	Manufacturer	Product rate/ha (kg)
1	Untreated control	-	-		-
2	Fluazinam 1.0	1.0	Shirlan (50%)	Crop Care (Aust) P/L	2.0
3	Fluazinam 2.0	2.0	Shirlan (50%)	Crop Care (Aust) P/L	4.0
4	Fluazinam 3.0	3.0	Shirlan (50%)	Crop Care (Aust) P/L	6.0
5	ICIA5504 1.0	1.0	(50% SC)	Crop Care (Aust) P/L	2.0
6	ZnO	20.0	ZnO (98%)	ICI	20.0
7	Mancozeb	16.0	Dithane (75% WP)	Crop Care (Aust) P/L	21.3
8	Flusulfamide 1.2	1.1	Nebijin (5%SC)	Mitsui Toatsu Chemicals Inc., Japan	21.9
9	Flusulfamide 1.8	1.6	Nebijin (5%SC)	Mitsui Toatsu Chemicals Inc., Japan	31.5
10	Potassium phosphonate (20%)	0.08	Foli-R-Fos 200	UIM Agrochemicals (Aust) P/L, Qld	4.0

Experimental treatments and design

Ten different treatments, including an untreated control and 9 fungicide treatments, were imposed on two different potato cultivars, Sequoia (susceptible to scab) and Snowgem (relatively tolerant to scab). Eight fungicide treatments were applied to soil and one to foliage (Table 8). Two cultivars of different relative susceptibilities to powdery scab were included in order to evaluate any possible interactions between cultivar and chemical treatments. Treatments were replicated 6 times (2 cultivars, 10 treatments, replicated 6 times). A row/column design was used (as distinct from a randomised complete block) to account for variation in the slope on the site in two different directions and because each cultivar had to be planted along an entire row length to facilitate planting by machine (see attachment).

Experimental procedure

The site was cultivated and soil formed into standard raised vegetable beds. Plots were 2 plant rows wide (1 bed width, 1.6m) and 10m long. All soil treatments, with the exception of zinc oxide, were applied to the surface of plots in a band 1.3 m wide using a hand-held boom spray with fan nozzles. Zinc oxide was applied to the surface of plots by watering can. Plots were rotary hoed after treatments were applied and cut seed potato setts of each cultivar planted by machine (2.5t/ha). Fertiliser was applied below the seed setts at planting at a rate of 620kg/ha: (Pivot Complete Fertiliser®, N:P:K, 1:1:1). Treatments were applied and seed planted on 14 June 1995. Plots were later side dressed with Pearl® fertiliser (N:P:K, 12:4.4:16.6) at 250kg/ha.

Potassium phosphonate treatments were sprayed onto the foliage of potato plants using a knapsack sprayer at intervals of approximately 14 to 20 days on the 12 and 26 September and 16 and 31 October 1995. Foliage was sprayed to run-off and the volume of spray applied increased as plants grew.

Plant sampling, yield and disease assessments

Plant sampling and tuber yield
The number of plants emerged was monitored at regular intervals after planting. Plants were sampled randomly from the border rows at weekly intervals after emergence to monitor the development of stolons and tuber set.

The crop was sprayed with desiccant herbicides in mid December to minimise tuber size. On the 15 and 16 January 1996 tubers were harvested by fork from 2m long borders at either ends of each plot and discarded. The remaining 6m of each plot was harvested by machine and tubers left on the soil surface. Tubers from each plot were sorted into the 4 size categories of 30-80g (chats), 80-250g (small), 250-450g (large) and >450g (oversize), counted and weighed. Tubers under 30g were not included in the assessment. Samples of 50 tubers from each plot (30 small and 20 large) were used for disease assessments. In plots where there were not enough numbers in the large size category, numbers were made up with tubers from the small category.

Disease Assessments
Disease incidence was recorded as the percentage of tubers with symptoms of the tuber blemishing diseases powdery and common scab, silver scurf, black dot and black scurf. Disease severity on each tuber was assessed as the % of tuber surface covered with each disease symptom. For powdery and common scab, disease severity was recorded as one of 13 categories of 0, <1, 2-5, 6-10, 11-20, 21-30, 31-40, 41-50, 51-60, 61-70, 71-80, 81-90 or 91-100% of tuber surface affected. The severity of silver scurf and black dot was recorded as severity ratings on a scale of 0-3 where 0 = no disease, 1 = <5%, 2 = 6-30% and 3 = >30% of surface covered. Symptoms of black scurf were also rated on a scale of 0-3 where ratings of 1, 2 or 3 were slightly, moderately or severely affected with black scurf. The

mean severity of powdery and common scab was calculated as the sum of the midpoint of each severity category multiplied by the number of tubers in that category, divided by the total number of tubers assessed. The mean severity of silver scurf, black dot and black scurf were calculated as product of each category rating and the number of tubers in each severity category multiplied by the total number of tubers assessed.

Total numbers of tubers, total yield and marketable numbers and yield (tubers in the categories 80-450g) from each plot were recorded. The proportion of marketable tubers with 0, ≤1% and ≤5%, representing different categories of marketable tubers with regard to disease levels, were also recorded. Tubers with up to 5% of their surface covered with powdery scab pustules may be tolerated in the fresh market, although the value of the produce can be downgraded with increasing levels of scab.

Statistical Analysis

Data was analysed using the REstricted Maximum Likelihood (REML) directive of the Genstat 5® statistical program, to analyse unbalanced designs. The Wald test was used to test the main effects and interaction of the cultivar and chemical treatment factors. The analysis was conducted on predicted, rather than actual means using pairwise comparisons.

Results

Of the two cultivars grown, Snowgem plants tended to emerge earlier and grow faster than those of Sequoia. Nine weeks after planting between 87% and 96% of Snowgem plants had emerged compared with only 11% to 15% of Sequoia plants. As a consequence, the initiation and development of tubers occurred later for Sequoia than for Snowgem.

There were no significant effects of chemical treatments on the number and yield of tubers produced by either cultivar. Snowgem produced more tubers per plot than did Sequoia. However, on average, Sequoia produced larger tubers and a greater proportion of marketable tubers than did Snowgem (Table 9).

The diseases powdery scab, common scab, black dot, silver scurf and black scurf were common on the skin of tubers at harvest (Table 10). There was no significant ($P>0.05$) effects of chemical treatments on the incidence and severity of diseases recorded for either cultivar. However, disease incidence and severity was affected by cultivar. The incidence and severity of powdery and common scab were higher ($P<0.05$) on Sequoia tubers (40% and 79% on average of tubers with powdery and common scab, respectively) than on Snowgem tubers (18% and 45%, respectively). The incidence and severity of black dot was unaffected by cultivar, whereas the incidence and severity of silver scurf and black scurf were higher on Snowgem tubers (13% & 21%, respectively) than on Sequoia tubers (5% and 10% respectively).

Although there were no overall significant effects of chemical treatments on disease incidence and severity, there were some apparent consistent trends in the data (Tables 11 & 12) when making pairwise comparisons of predicted means at $P=0.05$. Treatment with fluazinam tended to reduce the incidence and severity of powdery scab and increase the proportion of marketable tubers of Sequoia in the 0% scab and <1% scab categories compared with the untreated control. However, this trend was not apparent for Snowgem which had an overall lower incidence and severity of scab than Sequoia. Fluazinam had no apparent effect on the incidence and severity of common scab. The fungicide ICIA5504 tended to decrease the incidence and severity of both black dot and black scurf on Snowgem tubers but not on Sequoia tubers. Zinc oxide and the high rate of flusulfamide tended to increase the incidence and severity on black scurf in Snowgem but had no effect in Sequoia.

Discussion

None of the treatments evaluated in the trial reported here significantly affected the incidence and severity of powdery scab of potatoes, although soil treatments of fluazinam. flusulfamide, zinc oxide and mancozeb have all been reported to reduce the incidence and severity of powdery scab in field trials (Burgess *et al.* 1992, Burgess & Wale 1994, Braithwaite *et al.* 1994, Dixon & Craig 1994, Genet *et al.* 1996). A slight reduction in the incidence and severity of powdery scab on Sequoia after treatment with fluazinam indicates the potential of this fungicide to control the disease.

The reason for the lack of control of powdery scab and with the different chemical treatments in a light sandy soil is not known. A possible explanation is that fungicides were degraded or leached from the soil during the unusually long time between planting and emergence (more than 9 weeks). Dormant seed potatoes were planted at low temperatures in mid winter which delayed emergence and tuber initiation. Effective control of both powdery and common scab requires maximum concentrations of fungicides near developing tubers around the time of early tuber set when tubers are the most susceptible to infection. Secondly, fungicides were applied over the entire surface of plots and incorporated into the soil with cultivation which contrasts with the method of application in other trials where treatments were applied in a narrow band "in-furrow". Although rates per hectare are the same for both methods of application, the concentration of fungicide in the soil around the seed setts is less with the broad banding used in the trial reported here. Higher rates of application will have compensated for this discrepancy in concentrations resulting from this method of application.

Studies in Tasmania by the Tasmanian Department of Primary Industries and Fisheries (Ransom & Hingston 1991) have demonstrated the potential of fluazinam to control common scab of potatoes. A common treatment for the two diseases would be useful in areas were both powdery and common scab both affect the quality of potato tubers.

The fungicide ICIA5504, a systemic fungicide from the β-methoxyacrylate group, showed the potential to reduce the incidence and severity of both black dot and black scurf. This fungicide was the most effective in reducing early damage to potatoes caused by *Rhizoctonia solani* when compared with a range of standard treatments in a field trial in Victoria (de Boer unpublished data). This fungicide, which is active against a range of fungal groups (Heany & Knight 1994), may warrant further investigation in lieu of the limited number of fungicide seed treatments available in Australia at present, especially for the control of black dot.

The results of this trial suggest that the cultivar Sequoia is significantly more susceptible to both powdery and common scab than is Snowgem and this is consistent with other experience with the two cultivars elsewhere (Roger Kirkham, personal communication). Trends in the results of fluazinam treatments on powdery scab in Sequoia suggests that fungicide treatments could potentially provide greater returns if applied to a relatively susceptible cultivar rather than a relatively tolerant cultivar. The relatively low yield of Snowgem could be attributed to the lack of irrigation at the site of this trial. Snowgem requires consistent supplies of water to achieve maximum potential yields.

The fungicide potassium phosphonate, applied as a foliar spray, is used by potato growers as an intended cure for many disease problems including powdery scab and Rhizoctonia stem canker. In this trial, the fungicide had no significant effect on any of the diseases recorded. Other studies have also shown potassium phosphonate to be ineffective in controlling powdery scab (N, Shanmuganathan, T. Wicks, unpublished data).

Further trials are required to determine in what situations the fungicide fluazinam can be used most efficiently in terms of the influence of soil type, inoculum level and cultivar susceptibility on efficacy and subsequent marketability to tubers and economic returns.

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Table 9 Effects of different chemical treatments on the number and yield of tubers/plot of the cultivars Snowgem and Sequoia in a field trail at Torquay, 1995/96

Marketable tubers: 80-450g

Treatment	Total number of tubers/plot	Total yield of tubers/plot (kg)	Total number of marketable tubers/plot	Total yield of marketable of tubers/plot (kg)	% marketable number/plot	% marketable yield/plot
Snowgem						
Control	333.50	32.18	159.33	22.62	47.78	70.27
Fluazinam 1.0	353.67	34.43	185.33	25.43	52.40	73.87
Fluazinam 2.0	343.50	32.10	184.00	23.52	53.57	73.25
Fluazinam 3.0	374.33	34.84	188.67	24.94	50.40	71.59
ICIA5504 1.0	341.33	32.64	170.17	23.33	49.85	71.47
ZnO	344.50	32.66	168.33	23.21	48.86	71.06
Mancozeb	353.67	32.95	179.17	23.32	50.66	70.78
Flusulfamide 1.2	345.67	30.08	167.17	21.18	48.36	70.41
Flusulfamide 1.8	357.50	33.65	169.00	23.53	47.27	69.92
Foli-R-Fos 200	347.83	30.69	166.83	21.17	47.96	68.97
Mean	**349.55**	**32.62**	**173.80**	**23.22**	**49.71**	**71.16**
Sequoia						
Control	276.50	43.34	203.50	38.35	73.60	88.49
Fluazinam 1.0	298.33	42.16	229.83	37.58	77.04	89.12
Fluazinam 2.0	299.17	47.45	232.67	42.89	77.77	90.40
Fluazinam 3.0	300.00	46.30	229.83	41.54	76.61	89.71
ICIA5504 1.0	336.17	49.76	269.17	45.10	80.07	90.65
ZnO	287.83	46.79	222.50	42.20	77.30	90.19
Mancozeb	279.50	45.96	215.00	41.67	76.92	90.67
Flusulfamide 1.2	281.50	44.38	212.83	38.93	75.61	87.71
Flusulfamide 1.8	283.00	43.19	220.67	39.23	77.97	90.83
Foli-R-Fos 200	289.00	41.50	228.67	37.59	79.12	90.56
Mean	**293.10**	**45.08**	**226.47**	**40.51**	**77.20**	**89.83**

Table 10 Effect of chemical treatments on the incidence (% tubers affected) and severity of powdery scab, common scab, black dot, silver scurf and black scurf on the cultivars Snowgem and Sequoia in a field trial, Torquay 1995/96

Treatment	Powdery Scab		Common Scab		Black Dot		Silver Scurf		Black Scurf	
	% tubers affected	Severity (%)[A]	% tubers affected	Severity (%)[A]	% tubers affected	Severity[B]	% tubers affected	Severity[B]	% tubers affected	Severity[B]
Snowgem										
Control	18.07	0.34	37.34	0.83	65.41	0.75	10.93	0.11	16.94	0.17
Fluazinam 1.0	16.40	0.27	42.40	0.98	45.56	0.50	7.05	0.08	20.46	0.21
Fluazinam 2.0	19.15	0.35	52.50	1.90	63.53	0.71	12.40	0.22	20.87	0.22
Fluazinam 3.0	13.73	0.28	48.48	1.16	62.85	0.70	10.76	0.11	14.78	0.15
ICIA5504 1.0	25.80	0.64	47.82	1.09	55.37	0.62	12.21	0.12	2.36	0.02
ZnO	15.46	0.35	42.99	1.29	63.37	0.72	12.70	0.19	28.89	0.29
Mancozeb	20.38	0.34	38.57	1.04	58.25	0.71	15.03	0.18	28.77	0.29
Flusulfamide 1.2	18.69	0.30	41.54	0.97	65.47	0.81	12.57	0.13	22.39	0.23
Flusulfamide 1.8	17.01	0.37	46.82	1.18	68.10	0.78	21.93	0.29	31.54	0.32
Foli-R-Fos 200	15.77	0.38	49.62	1.48	62.63	0.69	9.41	0.10	24.55	0.25
Mean	**18.05**	**0.36**	**44.81**	**1.19**	**61.05**	**0.70**	**12.50**	**0.15**	**21.15**	**0.21**
Sequoia										
Control	48.77	2.24	77.33	3.23	68.96	0.89	8.37	0.09	8.03	0.08
Fluazinam 1.0	37.54	1.61	77.22	3.13	57.03	0.64	1.67	0.02	14.11	0.14
Fluazinam 2.0	28.17	1.47	84.67	4.23	53.33	0.61	3.00	0.03	7.00	0.08
Fluazinam 3.0	35.50	1.39	81.28	5.05	54.85	0.65	6.00	0.06	6.40	0.07
ICIA5504 1.0	41.14	2.17	79.23	3.61	37.11	0.42	4.73	0.05	6.01	0.06
ZnO	48.00	2.14	77.67	3.82	63.33	0.76	6.33	0.06	14.67	0.15
Mancozeb	40.55	2.22	86.65	4.03	60.80	0.75	2.00	0.02	9.72	0.10
Flusulfamide 1.2	39.76	1.37	74.56	2.16	59.52	0.70	6.67	0.07	10.38	0.10
Flusulfamide 1.8	44.67	2.32	79.67	5.57	60.67	0.78	2.67	0.03	10.00	0.10
Foli-R-Fos 200	39.84	1.45	74.42	4.48	55.23	0.66	5.03	0.05	10.01	0.10
Mean	**40.39**	**1.84**	**79.27**	**3.93**	**57.08**	**0.68**	**4.65**	**0.05**	**9.63**	**0.10.**

[A]Average proportion of surface area of tuber covered with powdery or common scab
[B]Severity rating scale 0 to 3: 0, no diseases; 1, <5%; 2, 6-25%; 3, >30% of tuber surface affected

Table 11 Trends in data showing the effects of different treatments on disease incidence and severity when compared with the untreated control using l.s.d. (P=0.05)

(Comparisons between predicted means only)

Treatment	Powdery Scab		Common Scab		Black Dot		Silver Scurf		Black Scurf	
	% tubers affected	Severity (%)	% tubers affected	Severity (%)	% tubers affected	Severity	% tubers affected	Severity	% tubers affected	Severity
Snowgem										
Fluazinam 1.0	-	-	-	-	-	-	-	-	-	-
Fluazinam 2.0	-	-	-	-	-	-	-	-	-	-
Fluazinam 3.0	-	-	-	-	-	-	-	-	-	-
ICIA5504 1.0	-	-	-	-	-	-	-	-	decrease	decrease
ZnO	-	-	-	-	-	-	-	-	increase	increase
Mancozeb	-	-	-	-	-	-	-	-	increase	increase
Flusulfamide 1.2	-	-	-	-	-	-	-	-	-	-
Flusulfamide 1.8	-	-	-	-	-	-	-	-	increase	increase
Foli-R-Fos 200	-	-	-	-	-	-	-	-	-	-
Sequoia										
Fluazinam 1.0	decrease	-	-	-	-	-	-	-	-	-
Fluazinam 2.0	decrease	-	-	-	-	-	-	-	-	-
Fluazinam 3.0	decrease	-	-	-	-	-	-	-	-	-
ICIA5504 1.0	-	-	-	-	decrease	decrease	-	-	-	-
ZnO	-	-	-	-	-	-	-	-	-	-
Mancozeb	-	-	-	-	-	-	-	-	-	-
Flusulfamide 1.2	-	-	-	-	-	-	-	-	-	-
Flusulfamide 1.8	-	-	-	increase	-	-	-	-	-	-
Foli-R-Fos 200	-	-	-	-	-	-	-	-	-	

Table 12 Trends in data showing the effects of different treatments on numbers and yield of tubers when compared with the untreated control using l.s.d. (P=0.05)

(Comparisons between predicted means only)

Treatment	% tubers in different categories of powdery scab severity			No. of marketable tubers/plot	% No. marketable tubers	Marketable yield	% marketable yield	Marketable yield with different categories of powdery scab severity		
	0 % scab	≤1% scab	≤5 % scab					0 % scab x	≤ 1% scab	≤ 5 % scab
Snowgem										
Fluazinam 1.0	-	-	-	-	-	-	-	-	-	-
Fluazinam 2.0	-	-	-	-	increase	-	-	-	-	-
Fluazinam 3.0	-	-	-	-	-	-	-	-	-	-
Fluazinam (Mean)	-	-	-	-	*increase*	-	-	-	-	-
ICIA5504 1.0	-	-	-	-	-	-	-	-	-	-
ZnO	-	-	-	-	-	-	-	-	-	-
Mancozeb	-	-	-	-	-	-	-	-	-	-
Flusulfamide 1.2	-	-	-	-	-	-	-	-	-	-
Flusulfamide 1.8	-	-	-	-	-	-	-	-	-	-
Foli-R-Fos 200	-	-	-	-	-	-	-	-	-	-
Sequoia										
Fluazinam 1.0	-	-	-	-	-	-	-	-	-	-
Fluazinam 2.0	increase	-	-	-	-	-	-	increase	increase	~
Fluazinam 3.0	increase	~	-	-	-	-	-	increase	increase	~
Fluazinam (Mean)	*increase*	~	-	-	-	-	-	*increase*	*increase*	~
ICIA5504 1.0	-	-	-	increase	-	increase	-	increase	~	-
ZnO	-	-	-	-	-	-	-	-	-	-
Mancozeb	-	-	-	-	-	-	-	-	-	-
Flusulfamide 1.2	-	-	-	-	-	-	-	-	~	-
Flusulfamide 1.8	-	-	-	-	-	-	-	-	-	-
Foli-R-Fos 200	-	-	-	-	~	-	-	~	increase	increase

6.3.3 Evaluation of chemical treatments for control of seed-borne powdery scab

Summary

Chemical dip treatments were evaluated for their effect on seed-borne powdery scab in a glasshouse trial. Treatments affected plant emergence, probably because tubers were physiologically old and had up to 5% of their surface covered with powdery scab pustules. No tubers (cv. Kennebec) treated with sodium hypochlorite or benzalkonium chloride sprouted, and between 1 and 6 out of 10 tubers treated with fluazinam, flusulfamide, fludioxonil, ICI5504 or formalin sprouted, compared with 8 out of 10 of the untreated controls.

An average powdery scab severity of 17% of tuber surface covered with scab pustules was recorded in the progeny of the untreated control seed. There were not enough replicates of the emerged treated tubers for a statistical comparison of the effects of chemical treatments with the untreated control. However, the incidence of tubers with scab after treatment with flusulfamide (average of 30% of tubers affected, 2% of surface covered) and formalin (30% of tubers affected, 0.2% of surface coverd) tended to be low relative to the untreated control.

This study demonstrates the potential of fungicide treatments to control control seed-borne scab. The study also shows the potential of evaluating chemical treatments for the control of seed-borne powdery scab in the glasshouse. This avoids the need to plant seed potatoes treated with powdery scab into uninfested ground on growers properties during the initial stages of evaluation of seed treatments.

Introduction

The current trend of planting potatoes into 'new' ground (not previously cropped with potatoes) has highlighted the potential of introducing *S. subterranea* into 'clean' soil on seed potatoes. A high proportion of seed potato production in soil with a history of potato cropping and of powdery scab. Although seed certification ensures that minimum standards are met for a number of soil-borne diseases, including powdery scab, some consignments may not be entirely free of tubers with the disease.

Tubers without scab pustules can be contaminated with spore balls of the fungus. Spore balls were found on the skin of tubers with no apparent pustules of powdery scab in a survey of seed potatoes (de Boer *et al.* 1982). Probable sources of this contamination include the soil in which tubers are grown, scabby tubers during sorting and storage (Harrison *et al.* 1993)and dust in sheds and stores (de Boer 1983). The risk of spreading the disease with the contaminated tubers is as high as with seed potatoes with scab pustules. In a glassshouse study, the incidence of progeny from seed tubers with 2-3%, or 10-15% of their surface covered with powdery scab was 84% and 71%, respectively, whereas 75% of the progeny of seed with no scab pustules were affected (R.F. de Boer, unpublished data). The apparently healthy seed was taken from amongst diseased tubers.

There are no registered treatments for the control of powdery scab on seed potatoes in Australia. Formalin is a common choice for growers wanting to treat seed that may be contaminated with powdery scab. This chemical is a potential carcinogen and is a very powerful biological fixative. There is an urgent need to find alternative chemicals that can reduce the risk of introducing the fungus on seed potatoes. The fungicide Shirlan (fluazinam) has been registered as a treatment for seed potatoes in New Zealand (Fallon, personal communication). Studies in New Zealand demonstrated that a number of chemicals, including fluazinam, formalin, mancozeb and dichlorophen-Na could increase the proportion of marketable tubers from diseased seed planted in uninfested soil (Braithwaite et al 1994).

The chemical treatment of seed may involve a number of different approaches, including treatment with disinfectants prior to storage, the application of protectant fungicides prior to storage or the application of fungicides after storage, but prior to, or at, the time of planting.

Chemical seed tuber treatments were evaluated in a glasshouse trial to obtain some preliminary data on the control of seed-borne powdery scab. Treatments included disinfectant chemicals and protectant fungicides. Tubers were dipped in solutions of chemicals for practical reasons. Ultimately, tuber spray or dust treatments need to be developed.

Materials and Methods

Whole seed potatoes of *cv* Kennebec with powdery scab, which had been stored at 1°C, were sorted in batches of even sized tubers (80-100g) with approximately 1-5% of their surface covered with scab pustules.

Tubers were placed in nylon mesh bags (10 tubers/bag), immersed for 2 minutes in 2L of fungicide solution (Table 13) in 10L-plastic buckets, then drained and allowed to dry. Treated potatoes were then planted, 10cm deep, into a moist seed raising mix (Debco) in 28cm diameter black plastic pots (one tuber/pot). Pots were arranged on glasshouse benches in a complete randomised block design of 9 treatments replicated 10 times. After plants emerged, pots were automatically watered to saturation every day through drippers delivering cold water (10°C) from a refrigerated tank. Irrigation scheduling ensured a minimum of 3 hours of cool (12-15°C), saturated soil each day, providing conditions favouring powdery scab. Pots were placed on saucers to slow drainage.

The majority of treated tubers failed to emerge after planting (Table 13). This is partly because tubers had broken dormancy when treated and had pustules of powdery scab making them susceptible to secondary rots and damage by the chemicals. However, pots in which plants had emerged were maintained in the glasshouse to assess the effectiveness of the irrigation system in providing conditions favourable to the development of powdery scab. At 14 weeks after planting, tubers were removed from pots, washed and assessed for the incidence and severity of powdery scab (Section 6.3.2).

Results and Discussion

Significant levels of powdery scab developed on the daughter tubers of untreated plants. On average 17% of the tuber surface was covered with scab pustules. Some tubers of this highly susceptible cultivar had up to 90% of their surface covered with powdery scab pustules. Insufficient numbers of the replicate plants emerged for a statistical comparison of the powdery scab in the treated and untreated controls. However, the severity of scab tended to be low after treatment with flusulfamide (2% of surface covered) and formalin (0.2% of surface covered) relative to the untreated control. Further studies using dormant seed are needed.

Tuber dip treatments are not practical on a commercial scale. They were used in this trial as a preliminary to further trials. Ultimately, treatments sprayed onto tubers will need to be evaluated.

This trial demonstrates the potential of evaluating treatments for seed-borne powdery scab the glasshouse as a preliminary to commercial testing. Treated seed must be planted in uninfested soil to avoid the confounding effects of soil-borne inoculum. Evaluation through glasshouse trials avoids the need to plant diseased seed in 'clean' soil on growers properties.

The effectiveness of disinfecting seed tubers on disease in the progeny depends on the level of inoculum already present in soil. Seed treatments will have most value in situations where seed is planted into uninfested soil or into soil with relatively low levels of inoculum. Where seed is to be planted into highly infested soil, seed treatments are unlikely to be of benefit except as a selling point by the seed grower.

Ultimately seed treatments must be part of an integrated management strategy for powdery scab to reduce the risk of spreading the pathogen into new areas or into fumigated soil.

Table 13 Seed potato dip treatments and their effect on plant emergence and seed-borne powdery scab in a glasshouse trial

Treatment	Active ingredient	Rate of product	No plants emerged (out of 10)	Tubers with scab (Diseased/Total)	Mean severity (% tuber surface covered)
Untreated control	-	-	8	29/35	17
Water	-	-	8	15/27	11
Shirlan®	fluazinam (500g/L)	40mL/L	1	2/4	2
Nebijin®	flusulfamide (50g/L)	40mL/L	5	5/17	2
Celest®	fludioxonil (100g/L)	10mL/L	5	14/22	9
ICI5504		20g/L	3	6/9	8
Phytoclean®	benzalkonium chloride 100g/L	20mL/L	0	-	-
Formalin®	formaldehyde (400 g/L)	5mL/L	6	4/17	0.2
Sodium Hypochlorite	sodium hypochlorite (125 g/L)	400mL/L	0	-	-

6.4 General Discussion and Conclusions

Alternative hosts and rotation

This study showed that *S. subterranea* can infect the roots of a wide range of plant species rotated with potatoes. These results are consistent with the results of others (Würzer 1965, Janke 1865, Jones and Harrison 1969, 1972). Inconsistencies between this and earlier studies (R.F. de Boer, unpublished data) may be related to differences in tests conditions. In summary, *S. subterranea* can potentially infect and produce zoosporangia in several species of grasses, cereals pasture legumes and fodder and oilseed brassicas used in Australian potato production systems.

Galls with cystosori, the survival spores of the fungus, were not found on the roots of the plant species that developed zoosporangia in our study, although they were reported to occur on the roots several species from the Solanaceae family under controlled glasshouse conditions elsewhere (Würzer 1965, Janke 1865, Blancard 1992). In our study, tests were conducted on seedlings which were harvested after only one infection cycle. Longer exposure to inoculum may give a better indication of the potential of these hosts to develop root galls.

We were unable, in the term of this project, to determine the function of the zoosporangial stage of the life-cycle on alternative hosts. Experiments were repeated because of lack of infection in controls early in the project, probably due to unfavourable test conditions and further studies are needed. Nothing is known of the ability of zoospores produced in sporangia to survive in soil but, unlike cystosori, they are probably short-lived and may not contribute to the long-term survival of the pathogen between successive potato crops. Without the production of spore balls the pathogen has not completed its life-cycle.

The discovery of zoosporangia and galls with spore balls on the roots of nightshade weeds in a potato field in Tasmania (Hoong Pung and R.F. de Boer, unpublished data) shows potential *S. subterranea* to survive indefinitely between potato crops on alternate hosts. Janke (1965) concluded, after a 3 years of field trials infested fields that such weeds were not important in the survival of *S. subterranea*. However, our knowledge to date suggests that the development of galls is restricted to close relatives of the potato and only occurs under conditions of extreme disease pressure (Blancard 1992). Without systematic studies in the field the importance of alternative hosts remain unclear.

Rotation

There was not evidence from field trials that crops preceding potato have a significant effect on the incidence and severity of powdery scab. However, more studies, which include measurements of the effects of cropping sequences of fungal inoculum, in a range of soil types and climates are needed. Natural fumigants released from *Brassica* species may provide an opportunity for control of the disease through rotation.

Rotations of 3 to 5 years are often recommended for the control of powdery scab buy experience Australia and elsewhere (Wale 1987) shows that 5 years is not enough. The reasons for this could include the apparent long term dormancy of spore balls which may have a staggered germination of cysts over many years, the presence of significant numbers of volunteer potatoes in rotations of 5 years or more and perhaps the presence of solanaceous weeds. It may take several years for the population of *S. subterranea* to decline after a potato crop if volunteer potatoes and weeds are controlled. However, rotations with as long a break as possible are critical in preventing the build-up of the population of the pathogen.

Chemical control

There were no significant effects of soil fumigation with metham sodium nor with a range of soil applied fungicides on the incidence and severity of powdery scab in the field trials conducted. Our results suggest that, due to farming practices, soil characteristics and climate, fumigation with metham sodium is not an economic proposition in the volcanic loams of the Central Highlands of Victoria. This treatment has potential, however, to reduce powdery scab other production areas but needs further evaluation. The reason for the lack of control with fungicides at Torquay may be due to the method of application, in this case sprayed over the whole plot surface area and rotary hoed in, effectively diluting the fungicide to below optimum rates, and the long interval between planting and emergence when fungicides may have been leached from the soil.

Fluazinam and flusulfamide are considered to be the two most promising treatments for powdery scab control (Dixon and Craig 1994, Genet *et al.* 1996). Soil treatment with fluazinam significantly improvements marketable yields in Australian trials conducted by Crop Care Australia (P.A. Taylor, personal communication). recently, researchers in the UK, achieved good control of powdery scab with flusulfamide (J.S. Wale, personal communication). These fungicides warrant further evaluation in Australia but need to be tested against a range of cultivars in different soil types, climates and cropping areas. It is not clear if these fungicides are more effective on highly susceptible cultivars compared with less susceptible ones, or more effective in soils with high disease potential compared soils with low disease potential. These fungicides perhaps provide one of the more tangible control options at present in the absence of a range of powdery scab resistant cultivars. Their relatively high cost (up to $600/ha for fluazinam) may restrict their use to high value markets such as seed and washed, fresh market potatoes). More work is need on better strategic application in soil and on rates of application.

The effectiveness of chemical treatments for seed potatoes can only be properly evaluated by planting diseased tubers untreated and treated) into uninfested soil to avoid the confounding effects of soil-borne inoculum. Planting diseased tubers on growers properties is not a desirable practice. The glasshouse screening test described here provides the option for the interim screening of chemical treatments under controlled conditions. Effective seed treatments would be part of good hygiene practice in the integrated management of powdery scab.

Integrated control

There is no one single treatment for the control of powdery scab. Several strategies need to be adopted to minimise the risk from disease including tolerant cultivars, hygiene, seed and soil chemical treatments, rotation, irrigation management and cultural practices. The adoption of various strategies involves a an assessment of the 'disease risk' associated with each of them. An important pre requisite for effective integrated management is the education. Growers with a good understanding of the pathogen, its life-cycle and the factors the influence the disease will be able to make informed decisions on disease control as part of their management of the farm and the potato crop.

Despite the possibilities of integrated management of powdery scab, this disease will remain a significant and difficult problem for the potato industry unless there is a concerted effort to understand the mechanisms of disease resistance and to screen and breed cultivars with high levels of immunity to this pathogen.

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WHAT'S NEW WITH POWDERY SCAB OF POTATOES

Megan Theodore

Powdery scab of potatoes is caused by the fungus *Spongospora subterranea*. Characteristic symptoms of the disease include white galls (like nodules on legumes) on the roots, stems and stolons and powdery scabs on the tubers. These contain masses of microscopic cystosori (`spore balls') each containing many spores.

Cystosori release swimming spores (zoospores) under cool (10-18°C, optimum 12-15°C) wet conditions. Soil must be saturated, either after rain or irrigation, so that spores can `swim' to potato plants to infect them. Under these conditions roots, stolons and below ground stems can be infected at any time. The fungus can multiply rapidly in the little hairs that cover the surface of roots producing new generations of zoospores within days of infection. Tubers, however, are only susceptible to infection during a critical period of about 3-4 weeks during early tuber initiation (`tuber set'). Thereafter tubers are mostly resistant to infection.

Disease Control Today

There are very few options for controlling powdery scab at present. Although potato cultivars vary in their susceptibility to powdery scab, most commercial cultivars grown today are very susceptible to scab. Russet Burbank is the least susceptible cultivar available.

There are no registered chemical control treatments. *The best options for control include planting cultivars with a low susceptibility and managing irrigation.* Experiments showed that withholding irrigation for a period of about 3 weeks around the time of early tuber set (1 week before, to 2 weeks after the time when 50% of stolons had swellings the size of a pea) reduced scab to very low levels compared with irrigating during this critical period. However, managing irrigation to control scab has limitations. The time of tuber set may not be uniform across a paddock of potatoes and, of course, there is the risk of rain during the critical period.

Current Research

Powdery scab is still a major problem for the potato industry in Australia and its incidence and severity is also increasing in other parts of the world. The disease threatens the viability of the seed and washed ware potato industries in particular, since the tolerance for scab on these commodities is very low. Active research is being conducted in New Zealand, United Kingdom, Switzerland and Australia.

New Zealand

Powdery scab has become an increasing problem for the New Zealand potato industry. Unlike Australia, where the disease is very widespread, there is still an opportunity to prevent the spread of the disease with effective seed treatments. Researchers with the Ministry of Agriculture and Fisheries evaluated several chemical treatments for the control of seed and soil-borne scab.

Chemical treatments that reduced the incidence of powdery scab in New Zealand

Seed treatments	*Soil treatments*
fluazinam	fluazinam
mancozeb	mancozeb
dichlorophen-Na	zinc oxide
dichlofluanid	zinc oxide & zinc sulphate

Infected seed was treated and planted in clean ground, or infested soil was treated with fungicides (in- furrow treatments) before planting. Several chemical treatments were found to significantly reduce the proportion of tubers with scab and increase the proportion of marketable tubers. Treatments that had some promise are presented in the Table above.

United Kingdom

The latest recommendations from the UK are geared towards the integrated control of the disease. Recommendations include:

- using cultivars with a low risk of developing scab
- plant healthy seed tubers
- choose ground which has a low risk of scab
- treat soil with zinc oxide

Zinc oxide treatments were the least effective when applied to very scabby soil planted with a very susceptible cultivar.

Switzerland

Powdery scab has been a major problem in potato growing regions of Switzerland for many years. Researchers have been developing tests (bioassays) for detecting *S. subterranea* in soils, both to determine if the soil is infected and what the `disease potential' of that soil is. By testing soils the Swiss have found that powdery scab is much more widespread than first thought. They are also developing biochemical tests to detect the fungus.

Australia

Research in Victoria, funded by the HRDC, is concerned with evaluating chemical control treatments and evaluating the possibility of reducing disease through rotation.

Alternative hosts and rotation:

Under artificial conditions *S. subterranea* can infect the fine hairs that cover the roots of many different plant species including clovers, grasses and rape. It is not clear if this happens in the field. Experiments are in progress to examine whether common rotation crops act as hosts of *S. subterranea* and if they in fact help the fungus to survive and multiply in the rotations between potato crops. Some plant species, such as brassicas (fodder rape, turnip, oilseed rape), may even eradicate the fungus through antifungal compounds released from the plants roots. The project aims to provide information and recommendations on rotations that minimise the carry-over of scab to the potato crop.

Chemical control:

The fungicide fluazinam has been trialed over several seasons in Australia by Crop Care Pty Ltd. The company aims to register this chemical for the control of powdery scab in the near future. A new chemical flusulfamide has shown potential to control powdery scab. Our research will evaluate this and other fungicides, including mancozeb and fluazinam, for the control of powdery scab. The effectiveness of soil fumigation with metham sodium against powdery scab is also being investigated in field trials.

The control of powdery scab will ultimately involve the integration of several options including less susceptible cultivars, careful choice of paddock, rotation, irrigation management and chemical control. Tests developed in the current research project could potentially be used to test the `disease potential' of growers paddocks.

Integrated Control

The control of powdery scab will ultimately involve the integration of several options, including less susceptible cultivars, careful choice of paddock, rotation, irrigation management and chemical control. Tests developed in the current research project could potentially be used to test the 'disease potential' of growers paddocks.

Scabby spuds

We are continually collecting scabby potatoes for use in glasshouse experiments, so if you have any potatoes with a high level of disease, and have no use for them, we would be happy to take them off your hands. If you have any experience regarding rotations and chemical control against powdery scab we would be interested in suggestions. Please contact either Megan Theodore or Rudolf de Boer on (03) 210 9222.

Powdery Scab - Can it be Controlled?

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Powdery scab is one of the most serious soil-borne diseases of potatoes in Australia today.

Caused by the fungus *Spongospora subterranea*, powdery scab is widespread throughout most of the traditional potato growing districts of Australia. The majority of the commercial cultivars grown today are susceptible to scab and there are no simple control measures for the disease.

Powdery scab is also a serious problem in other countries, most notably Switzerland, United Kingdom (particularly Scotland) and New Zealand where research programs on control are under way. Current research overseas includes the development of bioassays to detect the fungus in field soils and the evaluation of chemical treatments to control seed and soil-borne scab.

Research at the Institute for Horticultural Development (IHD) in Victoria is investigating the effects of alternative hosts and rotations on powdery scab as well as evaluating new fungicides for control. Also, the screening of new potato cultivars for resistance to scab is a routine part of the potato breeding program at IHD, Toolangi.

WHAT FACTORS FAVOUR THE DEVELOPMENT OF POWDERY SCAB?

Powdery scab is favoured by cool (12-18°C, optimum about 15°C), and periods of soil saturation after rain or irrigation. However, tubers are only susceptible to infection for a short period during early tuber set. If tuber set is defined as the stage when 50% of the new tubers developing on the stolons are the size of a pea, then tubers can only be infected by the fungus when cool and wet conditions occur during a period of about one week before tuber set to about two weeks after tuber set. After that stage tubers are essentially resistant to infection.

The severity of scab in a crop is also affected dramatically by cultivar. Powdery scab can almost completely cover the skin of one of the most susceptible cultivars *Kennebec*, but may occur as only a few scab pustules on the skin of one of the least susceptible cultivar *Russet Burbank*.

Soil pH can also affect scab and, generally, the disease is found to be less severe in the more acidic soils. Furthermore, researchers in Scotland have found that soils with more than six milligrams per kilogram of zinc tended to have a low incidence and severity of disease.

Other factors that are less understood include rotation, alternative hosts and paddock history. Powdery scab may occur consistently in some paddocks but not in others but we do not know what factors determine this.

CAN WE MANAGE THE DISEASE?

Some of the factors affecting scab can be manipulated, thereby providing some options towards managing the disease.

Resistant cultivars: The use of a resistant cultivar is the best option for control. However, only *Russet Burbank* and *Wontscab* can be considered relatively resistant. Most growers are forced to grow moderately to highly susceptible cultivars because of market demands. This is a particular problem for seed and ware markets which have low tolerances for scab. However, choosing a cultivar that has a relatively low susceptibility of scab can have a dramatic effect on the expression of disease in a crop.

Chemical control: There is renewed optimism for the chemical control option with the development of some new fungicides from Japan. In trials in the United Kingdom, New Zealand and Australia, fungicide treatments significantly reduced scab severity and increased marketable yields when applied to soil prior to planting.

Indications are, however, that fungicides will not be as useful when applied to highly susceptible cultivars planted in soil heavily infested with scab. They provide better returns when used with moderately susceptible cultivars in less severely infested ground.

Irrigation management: By managing the timing of irrigation we can exploit the critical period of susceptibility of potato tubers to infection by the scab fungus.

In several experiments, powdery scab was successfully reduced to very low levels by withholding irrigation over the critical 3 week period of susceptibility. The crop was watered up until one week before tuber set (as defined above) and not irrigated again until two weeks after tuber set without a significant yield penalty.

It is easy to dismiss irrigation management as a control option by saying that it is going to rain anyway. It is important to remember, however, that the critical infection period at tuber set only lasts three to four weeks. Rain in that period is not necessarily guaranteed.

However, there are limitations to this method of control. It is more suited to districts with a relatively low risk of early season rainfall. Some cultivars can be adversely affected by an irrigation deficit during early tuber set. Also, the timing of tuber set can vary from plant to plant in some crops and the critical infection period is spread out over a longer time.

More research is required to determine how the amount and frequency of rain or irrigation during tuber set affects the level of scab. This information will help us to predict more accurately the effect of water on the disease.

TOWARDS THE INTEGRATED MANAGEMENT OF POWDERY SCAB

There are options for managing powdery scab. However, for most growers there is no simple solution. In the absence of a range of resistant cultivars to choose from, growers should aim to manage the disease within acceptable tolerances using culti-

vars with low to moderate susceptibility. This should be integrated with other potential control options such as rotation, fungicides and irrigation.

An important step in deciding possible options each season is to assess the risk of growing a particular cultivar in a paddock that has had powdery scab. The Scots have been developing a prototype risk assessment scheme for powdery scab. By assigning points to different risk factors that contribute to scab, such as paddock history, cultivar, drainage, rainfall etc., they are hoping to be able to provide guidance on the risk particular paddocks present for the occurrence of scab. Systems being developed at IHD, Knoxfield, and in other countries, for testing soils for powdery scab could also help in this process.

In order to better manage powdery scab, farmers will need to understand something of the factors that govern disease development. It is up to the researchers to fill the gaps in our knowledge, particularly in the areas of rotation, chemical control, irrigation and on predicting disease in a particular paddock.

Various options for integrated control need to be evaluated in the field. These studies should be conducted with cultivars of varying susceptibility in a range of soil types with both high and low levels of infestation by the fungus so that the effects of the different management options can be predicted with more confidence. ■

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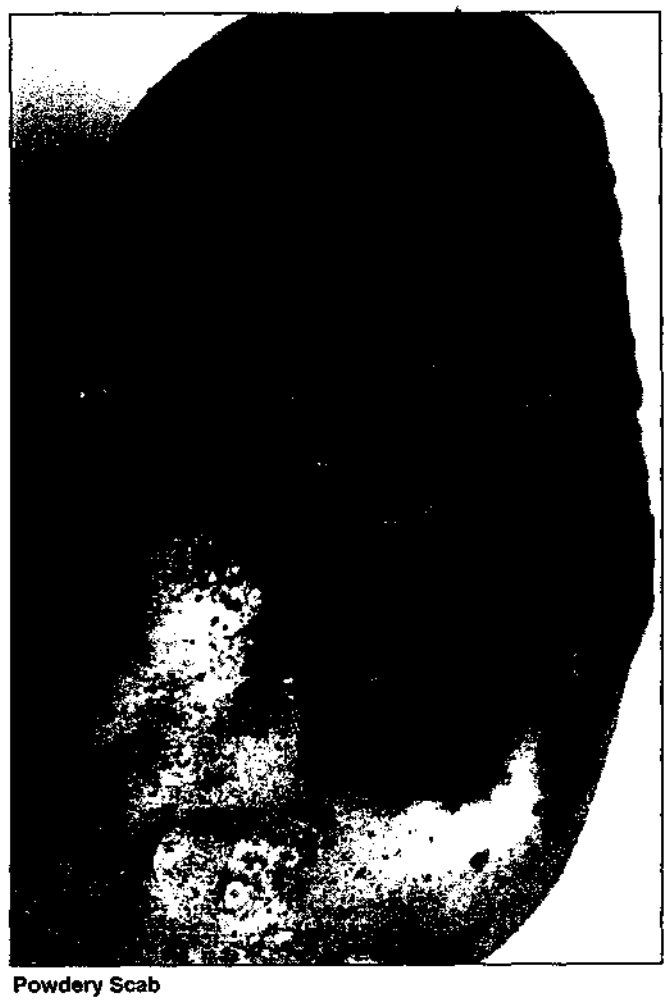

Powdery Scab

Options for Management of Powdery Scab

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1. Land Management and Selection of Cultivars

In paddocks with a history of scab use long rotations and plant cultivars with a low susceptibility to disease.
See table for susceptibility of cultivars to powdery scab.

The powdery scab fungus can survive in the soil in its dormant state for many years without the presence of a potato crop or any other plant. Crop rotation is essential to minimise the build up of the fungus in soil.

Although all commercially grown cultivars in Australia can be infected by powdery scab, there are marked differences in the levels of disease. Kennebec and Shepody are very susceptible while Russett Burbank shows low levels of scab.

2. Managing Irrigation

Wet, cool soils favour development of powdery scab. Tubers are most susceptible around tuber set and therefore, where possible, it is important to withhold irrigation during this period.
Refer to the diagram (overleaf) which explains timing of irrigation and tuber set.

Infection of potatoes by the powdery scab fungus (*Spongospora subterranea*) is favoured by wet, cool soils. The fungus requires free water to come in contact with potato tubers, roots or stems for infection and withholding irrigation at this time can dramatically reduce the risk of scab.
The preferred withholding period is from 1 week before tuber set to 2 weeks after tuber set.

There are limitations to this strategy which include heavy rainfalls around tuber set and in some crops not all plants set tubers at the same time.

Susceptibility of Potato Cultivars to Powdery Scab

Susceptibility	Cultivar
Very High	Crystal, Denali, Evans, Kennebec, Norchip, Pontiac, Sequoia, Shepody, Tasman, Toolangi Delight
Moderate to High	Bison, Coliban, Desiree, Red L Soda, Wilwash
Low to Moderate	Exton, Lindsay, Snowgem, Wilstore
Low	Atlantic, Sebago, Trent
Very Low	Russett Burbank, Tarago, Wontscab

Roger Kirkham, Megan Theodore & Rudolf de Boer, 1995. Institute for Horticultural Development, Agriculture Victoria, ph. (03) 9210 9222.