Breaking the critical-use barriers preventing Australian horticulture from phasing out methyl bromide

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Victorian Department of Primary Industries (VICDPI)

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BS04009

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BREAKING THE CRITICAL-USE BARRIERS PREVENTING AUSTRALIAN HORTICULTURE FROM PHASING OUT METHYL BROMIDE

Horticulture Australia Project: BS04009 (May, 2008)

Scott Mattner *et al.*

Department of Primary Industries, Victoria

Horticulture Australia Project BS04009 – Breaking the critical-use barriers preventing Australian horticulture from phasing out methyl bromide

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Purpose of Project

Australian horticulture continues to face one of its greatest challenges of the modern era – the phase-out of methyl bromide (MB) due to its ozone depleting properties. For 50 years, the industries had used MB to disinfest soils of pathogens, weeds and pests, and to maximise yields. This project was conducted to identify alternatives for industries applying to the UN for critical-use exemptions to retain MB use (especially strawberry runners, strawberry fruit, and flower industries). It evaluated novel production methods that mitigate the need for soil disinfestation, including soil-less production and tissue culture, in addition to alternative soil fumigants. The future integration of these treatments offers growers a mechanism for reducing their reliance on chemical fumigation, increasing the efficacy of alternative fumigants, improving soil health and increasing the sustainability of their industries. Through this research, the number of industries applying for CUEs has fallen by 80% since the commencement of this project, and MB use in Australia has decreased by 110 tonnes pa. The identification of alternatives to MB through this and previous projects has prevented losses in Australian horticulture worth over $100 million annually.

Acknowledgments

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May 2008

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1 Media Summary

This project has provided horticultural industries with a number of options to better manage the health of their soil using ozone-friendly practices. For the past 50 years, horticultural industries have relied on methyl bromide (MB) to disinfest their soil of the pathogens, weeds and pests that reduce yields. However, MB is a powerful ozone depleter (60 times more destructive to the ozone layer than CFCs) and has been mostly phased-out in Australia and other developed countries under the *Montreal Protocol*. A previous 10-year research program funded by HAL identified a range of ozone-friendly strategies, such as 1,3-dichloropropene/chloropicrin, chloropicrin, steam, and substrates that could replace MB in many Australian horticultural industries. However, these alternatives were unsuitable for some crops and further commercial studies were required on different application methods and new products. To address these issues, this project aimed to develop new soil management strategies for five Australian horticultural industries (including strawberry runners, strawberry fruit and protected flowers), which had applied to the UN to retain the use of 140 tonnes of MB *per annum*. The project formed a strong collaboration with a similar program in New Zealand and conducted extensive research on: (1) new ozone-friendly soil fumigants (eg methyl iodide); (2) new production systems that avoid the need for soil fumigation with MB (based on hydroponics, soil-less media and micro-propagation); (3) a range of biological and non-fumigant options for treating soils (eg composts, biofumigants, and herbicides); (4) better understanding the application and environmental conditions that optimise the effectiveness of alternatives (eg plant-back times for new fumigants); and (5) methods to reduce emissions of exempted MB and other fumigants to the atmosphere. Additionally, participatory trials were conducted with a range of alternatives to improve grower's confidence in their use.

At the completion of this project, the number of Australian horticultural industries applying to retain the use of MB has fallen by 80%, and overall use has dropped by 110 tonnes *per annum*. Adoption rates of alternatives in Australia have been faster than in similar industries worldwide, and this has increased Australian horticulture's reputation for sustainable production practices and environmental stewardship. As acknowledgement of this, in 2006 and 2007, industry and the project team won international awards for ozone protection from the US EPA and the UN Environment Programme.

In the past, the use of MB for soil disinfestation prevented yield losses of 35%, worth over $100 million annually, due to pests and weeds. By adopting alternative soil treatments to meet MB phase-out targets, growers have not only maintained yields, but have contributed to the 45% reduction in bromine concentrations measured in the lower atmosphere in southern Australian since the commencement of the MB alternatives program. The good news is that the elimination of substances like MB will see the ozone hole start to shrink in the next few years, and restore itself some time in the middle of this century. This will be the first time in history that humankind has reversed an environmental disaster of such proportions.

2 Technical Summary

This project aimed to develop alternatives to the ozone-depleting fumigant, methyl bromide (MB), for five horticultural industries that held critical-use exemptions to retain its use (Queensland strawberry fruit, Victorian strawberry fruit, Victorian and Queensland strawberry runners, Queensland protected flowers, and Victorian protected flowers), and two industries that were considering applying for them (Australian turf industries, Victorian tobacco industry). More than 20 field trials were conducted across Australia and New Zealand in the strawberry industry alone, examining combinations of eight fumigant and nine non-fumigant treatments, and two new production systems as alternatives to the use of MB. Major scientific and technical outcomes included:

- The alternative fumigant, methyl iodide (MI), potentially offers horticultural industries a robust, long-term alternative to MB. In strawberry fruit and runner trials, it consistently delivered equivalent yields, and disease and weed control to MB across a range of environments. If MI achieves registration and is economical, it is likely to replace the last remaining uses of MB in Australian horticulture.
- Under optimal environmental conditions, the registered alternative fumigants, Telone C-35 and chloropicrin, consistently produced equivalent strawberry fruit and runner yields to MB. Consequently, most Australian and New Zealand strawberry fruit growers have adopted these products to replace their use of MB. However, in trials conducted in cold (< 10°C), wet and/or compacted soils, these fumigants resulted in crop phytotoxicity; lower yields; and/or inferior pathogen, weed and disease control compared with MB. These efficacy problems related to longer residual times of Telone C-35 and chloropicrin in soils due to their higher boiling points and lower vapour pressures of (1,3-dichloropropene: 104°C, 3.1 kPa, chloropicrin: 112°C, 2.25 kPa) when compared with MB (4°C, 190 kPa). These results have demonstrated the importance to growers of applying all alternative fumigants under optimal environmental and edaphic conditions in order to maximise product efficacy.
- Alternative production systems based on the use of hydroponics, soil-less media and micro-propagation technologies have potential for replacing the need for small amounts of MB (c. 8 tonnes pa) in the strawberry runner industry. For example, fruit yields from plug transplants produced in soil-less media ranged from 60% above to 30% below the yields of bare-rooted runners produced in MB-treated soils. Further research is needed to better understand the physiology of plug transplants before they could deliver fruit growers consistently high yields.
- A range of non-fumigant approaches to treating soils failed to deliver the high crop yields or disease control achieved in MB-treated soils. For example, strawberries grown in soils amended with high N inputs (urea), composts, biofumigants (eg mustard oil), and biological controls (Trichoderma formulations) yielded 40-60% less fruit than plants in MB-treated soils. However, the long-term effects of these treatments on soil health and resilience to pathogen re-colonisation warrants further investigation.
- The post-emergent herbicide, isoxaben, reduced weed emergence by 63% without causing phytotoxicity in strawberry crops. This highlights its potential as a

complimentary treatment to deliver improved weed control with some alternative fumigants, provided future trials continue to demonstrate no adverse effects against strawberry plants.

- Gastec™ indicator tubes and lettuce tests generally provided good estimates (within of the plant-back times (the time needed between treatment and planting to avoid fumigant phytotoxicity) needed for alternative fumigants. The use of Gastec™ indicator tubes provides growers with instantaneous readings of the concentrations of fumigant residues present in soil, and may form an additional tool (in addition to fumigant label recommendations) for predicting when it is safe to plant crops after fumigation.
- Impermeable barrier films (eg polyethylene/polyamide laminates or aluminised polyethylene) were found to be 10 times more effective in preventing MB emissions to the atmosphere than standard low-density polyethylene (LDPE). For industries that retain plastic mulch on soils for the entire growing season (eg tomatoes, melons, capsicums, strawberry fruit), impermeable barrier films offer an environmentally-responsible mechanism for allowing reduced application rates of fumigants. For broad-acre horticultural industries (eg strawberry runners) that cut and remove films shortly after treatment (ie less than week), the use of impermeable barrier films may pose a potential off-gassing and OH&S issue for operators. However, trials in the strawberry runner industry showed that standard application rates of MB (500 kg/ha of MB:Pic 50:50) have the potential to be reduced by up to half without affecting efficacy against pathogens and weeds, or final yields.
- This project communicated technical outcomes to scientific audiences through the publication of 7 journal papers, 21 conference papers, and 10 scientific reports.

3 Adoption of sustainable, ozone-friendly practices for soil disinfestation in Australian horticulture

3.1 The global phase-out of methyl bromide for soil disinfestation

Soil disinfestation is the process of reducing or controlling pathogens, weeds, nematodes and pests in soil prior to planting crops. For 50 years, methyl bromide (MB) has been the most widely used and effective fumigant for soil disinfestation in the world. However, the bromine from MB is 60 times more efficient at destroying ozone than the chlorine from the well known ozone-depleters, chlorofluorocarbons (CFCs). For this reason, MB was added to the *Montreal Protocol on Substances that Deplete the Ozone Layer* and was scheduled for phase-out for soil disinfestation purposes in developed countries, including Australia, in 2005. Without the restrictions on MB use, bromine levels were expected to increase in the atmosphere by ten-fold by mid-2050 (compared to 1980 levels) resulting in extensive worldwide ozone depletion.

3.2 Environmental and social benefits of MB phase-out

The ozone layer is a concentrated band of ozone contained in the stratosphere, which surrounds the earth. The ozone layer is vital to life because it absorbs most of the sun's damaging ultraviolet radiation, particularly UV-B. In the early 1980s, scientists measured a thinning of the ozone layer, and the development of 'ozone holes'. Since then, ozone levels have continued to fall and in 2000 the ozone hole over Antarctica reached its largest size ever – 30 million km^2.

Ozone depletion has enormous consequences for Australia due to its close proximity to the Antarctic ozone hole. Australia has the highest incidence of skin cancer in the world, with 1 in 2 people contracting the condition at some stage in their life. This costs the health system in excess of $300 million per year. The degradation of the earth's ozone layer is possibly one reason for the increasing rates of skin cancer in Australia. Ozone depletion has many other serious environmental consequences, with the potential to reduce our native biodiversity and interact with the effects of global warming.

The elimination of MB from horticultural industries is expected to have a 5-15% effect in restoring the ozone layer and reduce the incidence of skin cancer significantly. Already the restrictions on MB use (50% reduction in 2001 and 70% in 2003) in Australia have had positive effects, reducing bromine concentrations in the atmosphere in southern Australia by 45% (Fig 3.1), and this is having immediate benefits for ozone restoration. Full implementation of the *Montreal Protocol* will mean that the ozone layer will restore itself sometime in the middle of this century. This will be the first time in history that humankind has been able to fully rectify an environmental disaster of such proportions.

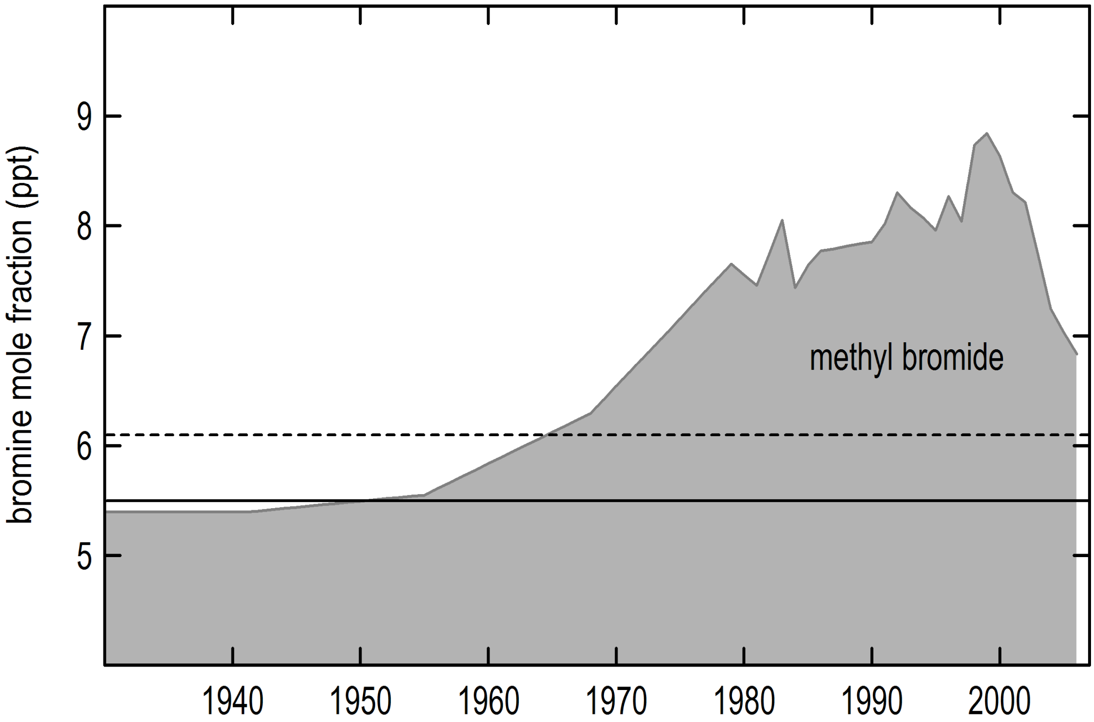


Figure 3.1. Historical concentrations of bromine in the atmosphere in Southern Australia – restrictions on MB use have reduced bromine concentrations by about 45%.

3.3 Status of MB in Australia in 2005

The announcement that MB was being phased out was the biggest threat of the modern era to Australian horticultural industries (eg tomato, capsicum, cucurbits, strawberries, flowers, turf) valued at over $300 million pa. Without a suitable replacement, these industries stood to lose 35% in yields or $110 million annually. Moreover, this loss would have been considerably greater in the event of severe disease epidemics.

From 1995, a National MB Research and Communication Program was initiated that aimed to identify alternative soil disinfestation systems for industry by the phase out deadline of 2005. The program conducted more than 100 trials nationally investigating more than 20 fumigant alternatives (eg 1,3 dichloropropene, chloropicrin, dazomet, metam sodium) and 40 non-fumigant alternatives (eg solarisation, steam, biofumigants, integrated pest management, herbicides, fungicides). For most industries, the development of these alternatives allowed growers to cease use of MB by 2005 without significant increases in pest and disease pressure on-farm or loss in profits.

Under the terms of the *Montreal Protocol*, industries that can demonstrate they have no technically or economically feasible alternatives to MB can apply annually to the UN for a critical-use exemption (CUE) to retain its use. In 2005, when this project commenced, five Australian horticultural industries had applied for, and been granted, CUEs to retain MB for soil disinfestation purposes: the Victorian strawberry fruit industry, the Queensland strawberry fruit industry, the Victorian and Queensland strawberry runner industry, the Victorian protected flower industry and the Queensland protected flower industry. In total, 140 tonnes of MB were granted to Australian horticulture for soil disinfestation purposes under CUEs (Table 3.1). Additionally, other industries (turf and tobacco) were having difficulties in implementing alternative practices and were considering applying for future CUEs.

Table 3.1. Use of MB for soil disinfestation in Australian horticulture in 1995 (the announcement of MB phase out), 2005 (the scheduled phase out date), and 2010 (critical use exemptions, CUEs, granted at the time of the completion of this project).

Horticultural Industry	1995 MB use (tonnes)	2005 CUE MB allowance (tonnes)	2010 CUE MB allowance (tonnes)	MB alternatives adopted
Vegetable (tomato, capsicum)	229	0	0	rotation; IPM; 1,3-D / Pic; metam sodium
Flowers	175	35.8	0	Soil-less substrates; steam; IPM; 1,3-D / Pic; Pic
Strawberry fruit	106	67	0	Pic; 1,3-D / Pic; metam sodium
Protected horticulture	50	0	0	Soilless substrates; steam; IPM; dazomet; 1,3-D / Pic
Melons	40	0	0	1,3-D / Pic; metam sodium
Strawberry runner	36	35.75	29.79	low concentration MB; rotations; soilless substrates for propagation generations; likely to adopt methyl iodide if it becomes registered
Turf	18	0	0	Dazomet
Orchard Replant	10	0	0	Pic; dazomet; 1,3-D / Pic
Tobacco nursery	5	0	0	Semi-hydroponics (flotation trays)
Others (eg pineapple, nursery)	10	0	0	Various
TOTAL	**679**	**138.55**	**29.79**	

3.4 Project aims

Research and communication activities in this project aimed to assist horticultural industries holding CUEs for MB in 2005 to transition to alternative soil disinfestation systems. To achieve this, researchers collaborated with other projects in the National MB Research and Communication Program (BS04005; BS04005; HG01005; HG01045; HG04018; TB04001), and with similar programs in New Zealand. Key activities conducted to support industries' transition to MB alternatives, included:

- Research trials on the key alternative fumigant, methyl iodide (MI), to generate data in support of its possible registration in Australia;
- Commercial trials with alternative fumigants (1,3 dichloropropene, chloropicrin and methyl iodide) to increase grower confidence in their application and efficacy;
- Research trials on emission controls and associated lower application rates of exempted MB;
- Trials on the relative efficacy of alternative fumigants against natural populations of soilborne pathogens;
- Trials on alternative production systems that eliminate or reduce industries' reliance on MB and other fumigants
- Long-term trials to understand the efficacy of alternative fumigants applied annually to the same soil;
- Plant-back trials with alternative fumigants to assist growers in knowing how long to wait after treatment before planting their crops;
- Communication activities to increase grower awareness of MB alternatives, their benefits and limitations, and application techniques.

3.5 Change in MB use by 2008

Use of MB in Australian horticulture has fallen by more than 95% since the phase-out announcement in 1995. Furthermore, the number of horticultural industries applying for CUEs has dropped by 80% since the scheduled phase-out date in 2005, with a proportionate decrease in total MB use (Table 3.1). Adoption rates of MB alternatives in Australia have been faster than in similar industries worldwide, and this has increased Australian horticulture's reputation for sustainable production practices and environmental stewardship. The following discussion summarises how industries holding CUEs in 2005, or contemplating applying for them, transitioned to MB alternatives:

Queensland and Victorian Strawberry Fruit

In 2005, the strawberry fruit industry applied for, and was granted, a CUE to retain the use of 67 tonnes of MB pa. The industry cited a lack of commercial-scale trials demonstrating the efficacy of alternative fumigants as the main reason they needed to retain MB. To address this, this project conducted grower trials and workshops nationally to increase grower confidence in using the alternatives. It also conducted trials demonstrating efficacy of alternatives against natural populations of pathogens. These factors were critical in assisting industry adopt the alternative fumigants 1,3 dichloropropene / chloropicrin (Telone C-35) and chloropicrin. By 2006, the industry had fully transitioned to these alternatives and ceased applying for CUEs. This was amongst the fastest rates of adoption of MB alternatives by strawberry industries worldwide, and earned the Australian industry the 2006 Ozone Protection Award and 2007 'Best of the Best' award from the USA's Environmental Protection Authority.

Queensland and Victorian Protected Flowers

The protected flower industry applied for CUEs to retain the use of MB for soil disinfestation until 2008. They cited a lack of application technologies for applying alternative fumigants within the confined spaces of glasshouses as the main reason they needed to retain MB. Since 2005, industry has further developed and adopted soil-less substrates and steam disinfestation of soil, identified in previous HAL projects (HG01045), to suit most cropping and production systems. However, this project has also assisted in developing drip fumigation techniques (results reported in HG04018) that will allow growers the technologies needed to treat soils in confined glasshouses. It is anticipated that these technologies will become available to growers following 2008.

Turf

By 2005, the turf industry had adopted dazomet and metam sodium as alternatives to MB, due to their strong efficacy against weeds compared with other registered alternatives. However, both of these products were failing to fully control volunteer grasses from the previous crop. This became an issue for industry when producing elite lines that required 100% control of the previous crop under PBR guidelines. Consequently, industry was contemplating applying for CUEs for MB to meet this niche production requirement. To address this, this project assisted in developing new alternative fumigants (MI formulations) with greater efficacy against grass species (results reported in HG04018). The imminent registration of these products assisted in convincing industry to withhold applying for CUEs.

Tobacco

By 2005, almost all of the Australian tobacco industry had ceased production of transplants in disinfested soils and had moved to semi-hydroponics production systems. This move significantly reduced the need for MB (by more than 95%) and other soil fumigants, but the system still relied on MB to disinfest polystyrene seedling trays. For this reason, industry was considering applying for a CUE to retain small amounts of MB for this use. To address this, this project assisted in developing alternative tray disinfestation systems based on the integrated use of improved hygiene, pressure washing, and solarisation (results reported in TB04001). By the end of 2006, growers accepted an industry buy-out to cease tobacco production in Australia. However, the research conducted has implications for tray disinfestation in other industries, such as hydroponics vegetables.

Strawberry Runners

In 2008, strawberry runners are the only Australian horticultural industry still applying for CUEs to retain MB. Their difficulties lie with the reduced efficacy (ie pathogen and weed control) and increased risk of crop losses (from fumigant-induced phytotoxicity) from currently registered alternative fumigants under the cold conditions and the high elevations needed to grow strawberry runners. This is due to the significantly higher boiling points and lower vapour pressures of registered alternative fumigants compared with MB. For example, some alternative fumigants have caused crop losses of more than 30% due to their long residual times (longer than 3 months) in cold soils (BS01004, Section 4.4). In addition, high phytosanitary requirements need to be met to grow certified runners, and this has created greater pressure to find a better one-to-one alternative to MB for disease and weed control. To address this, this project conducted trials to better understand the plant-back times (the period between fumigation and planting a crop) needed for alternative fumigants, pathogen efficacy studies, and trials on MI which has a lower boiling point and higher vapour pressure than other registered alternative fumigants. It is anticipated that the strawberry runner industry will transition to MI if it becomes registered in Australia.

3.6 MB phase out: the final steps

To assist in expediting MB phase out in Australia, HAL funded a review and facilitated workshops to identify the barriers preventing the strawberry runner industry adopting alternatives, and the research and communication activities required to assist the industry in moving towards alternative systems. The barriers identified included: (1) increased risk of crop losses from phytotoxicity with currently registered alternative fumigants, (2) the inferior efficacy of these products against pathogens and weeds, and (3) the associated threat to the health status and biosecurity of the fruit industry. The HAL review identified the following priority areas for future research: (1) commercial scale-up trials of MI to support its registration and certification approval; (2) emission control strategies to support reduced rates of exempted MB and other fumigants; (3) development of new alternative fumigants in the case that registration of MI fails in Australia; and (4) research on soil-less systems for the production of strawberry runners. These research priorities are being taken up in new HAL-funded research project (BS07014) that will provide the strawberry runner industry the best prospect for phasing out MB without compromising the high health status or profitability of the strawberry fruit industry. It is anticipated that this new project will see the end to the use of MB in Australia, an end to CUE applications and the completion of a successful 12-year National Research and Communication program to phase out MB for soil disinfestation.

4 Methyl bromide alternatives: Australian research trials

4.1 Summary

A series of trials were conducted in the Australian strawberry runner and fruit industries on alternative fumigants and production systems to MB. These trials have provided several future directions to assist the strawberry runner industry move towards MB phase-out (eg the use of methyl iodide or alternative production systems utilising hydroponics, soil-less media and micro-propagation technologies). In addition to scientific trials, participatory grower trials conducted in the strawberry fruit industry were important in increasing the confidence of growers in the application and use of alternative fumigants, and assisted the industries' rapid phase-out of MB. The high adoption rates of alternatives earned the Australian strawberry fruit industry international recognition for ozone protection.

Key findings from the research were:

- The alternative fumigant, methyl iodide (MI), potentially offers the strawberry runner industry a robust, long-term alternative to MB. In trials, it consistently delivered equivalent pathogen and weed control, and runner yields to MB across a range of environments. If MI achieves registration and is economical, it is likely to replace MB for runner production.
- The alternative fumigants Telone C-35 and chloropicrin provided equivalent or better strawberry fruit yields to MB in grower trials. Consequently, these products formed the backbone of the industries' strategy to phase-out MB. However, under the colder/wetter conditions in the strawberry runner industry, residues of Telone C-35 persisted for long periods in soils and caused fumigant-induced phytotoxicity in runner plants in some trials. Also, Telone C-35 did not consistently control strawberry pathogens or weeds to the same level as MB under these conditions. We hypothesise that new formulations of Telone that contain lower concentrations of 1,3-dichloropropene and higher concentrations of chloropicrin may be more suitable for use in the runner industry.
- The post-emergent herbicide, isoxaben, reduced weed emergence by 63% without causing phytotoxicity in strawberry crops. This highlights its potential as a complimentary treatment for improved weed control with some alternative fumigants, provided future trials continue to demonstrate no adverse effects against strawberry plants.
- Gastec™ indicator tubes and lettuce tests provided a conservative estimate of plant-back times for alternative fumigants in the runner industry, and therefore may provide growers with an additional tool (in addition to label recommendations) for predicting when it is safe to plant their crops after fumigation.
- Alternative production systems based on the use of hydroponics, soil-less media and micro-propagation technologies have potential for replacing the need for small amounts of MB in the runner industry. However, further research is required to better understand the physiology of fruiting plants produced using these technologies before they could deliver fruit growers consistently high yields.

4.2 Introduction

This chapter summarises research conducted in Australia to assist industries holding CUEs in 2005 move to MB alternatives. Research presented in this chapter was conducted in the strawberry runner and fruit industries. Results of research in additional industries are presented in other HAL final reports (turf HG04018, flowers HG01045 and HG04018, and tobacco TS04001). This latter research: (1) supported a registration application for the alternative fumigant, methyl iodide (MI), for turf production; (2) evaluated remote application systems for applying alternative fumigants in the protected flower industry; and (3) developed integrated disinfestation systems (based on improved hygiene, pressure washing and solarisation) for seedling trays in the tobacco industry.

4.3 General Methods

Field trials in strawberry runners were established at Toolangi, Victoria on a site adjacent to a commercial runner bed with a silty clay soil. The site had no history of fumigation or strawberry production. Trial beds were prepared and maintained for runner production using practices as close to the industry standard as possible. Trials were conducted on flat rows (2.7 m width), which were broad-acre fumigated (by fumigant contractors: Statewide Fumigation Services and R&R Fumigation, Bayswater, Victoria) following normal soil preparation (rotary hoeing). Individual plots were between 25-60 m in length. All fumigants were shank-injected into soil to a depth of 20 cm and the soil surface sealed with LDPE (low-density polyethylene) or low-permeability barrier film. A buffer zone of 1 m was used between rows and plastic film was dug into the soil at the end of each treatment to minimise fumigant movement between plots. About 1-2 wks after fumigation, barrier film was removed and the soil allowed to air prior to planting. Plots were planted by hand with a single row of strawberry runners (mother stock) spaced 0.5m apart.

Strawberry fruit trials were conducted at Coldstream, Millgrove, Main Ridge and Wandin, Victoria; and Wanneroo, Western Australia; on commercial farms. Trials were on raised beds (0.8m Vic, and1.2m width WA), which were fumigated following soil preparation and bed raising. All fumigants were applied using a strip fumigation technique. In this technique fumigants were injected to a depth of 20 cm into preformed beds through tynes spaced 20 cm apart, and then covered with black LDPE film. The film remained in place for the entire growing season. Trials in Victoria used two-row beds, while those in WA used a four-row bed, with plants in trials spaced c. 400 mm apart. All other agronomic practices followed industry standards. All sites had a history of strawberry production and previous fumigation with MB.

Data were analysed using analysis of variance (ANOVA), non-linear regression and correlation analysis as performed on the GENSTAT 10.1 statistical package (Lawes Agricultural Trust, IACR Rothamsted). Homogeneity of variance was determined by examining plots of fitted values versus residuals, while histograms of residuals assessed normality of distribution. Where variance was heterogenous, appropriate data transformations were made to restore homogeneity. Fischer's least significance difference test (LSD 0.05) was used to identify significant differences between treatment means.

4.4 Long-term Fumigant Use (Toolangi, Vic; 2002-2008)

Aim: To determine the efficacy of repeated treatments in the same soil of alternative fumigants compared with MB over successive years, for strawberry runner production.

Treatments: MB:Pic (50:50) (500 kg/ha)
Telone C-35 (500 kg/ha)
Chloropicrin (500 kg/ha), years 1 and 2
MI:Pic (30:70) (500 kg/ha), years 3 and 4
Untreated (Control)

Design: 50 m long plots
Randomised complete block design with three blocks

Variety: Camarosa (planted at least 3 months after fumigation, single row spaced 50 cm apart)

Method: This trial was conducted from 2002 to 2008 (five years/seasons). During this period, fumigants were applied annually to the same soils and used to grow strawberry runners. Plots were fumigated between May - June each year, planted between August - October (ie a plant-back of at least 3 months) and harvested April - May (7-8 month growing cycle). Emergence of natural populations of weeds was recorded through the season as the number of individual species contained in five random 0.16 m^2 quadrats per plot. At harvest, all runners in each plot were dug with a potato harvester and the total fresh weight of runners recorded. In year 3 of the trial, plots previously fumigated with chloropicrin were switched to MI treatments. This is because results showed that weed control with chloropicrin was insufficient to allow certification of strawberry runners, and because of the recent importation of MI into Australia with reported superior broad-spectrum activity against weeds and pathogens.

Results / Discussion:

Chloropicrin: Although runner yields in soils treated with chloropicrin were equal to those in MB-treated plots (Fig 4.1), weed control was poor and insufficient to meet runner certification standards (Fig 4.2). This means that complimentary treatments (see Section 4.5) that improve weed control (eg herbicides) in chloropicrin-treated soils would need development before runner growers could use it as an alternative to MB.

Telone C-35: Runner yields in Telone C35-treated plots were significantly below (30%) those in MB-treated plots in two out of the five years of this trial (Fig 4.1). In these years, runners grown in Telone C35-treated plots showed symptoms consistent with fumigant-induced phytotoxicity (ie roots of mother plants were dead and plants survived by producing new roots from the aerial section of the crown). This phytotoxicity probably relates to longer

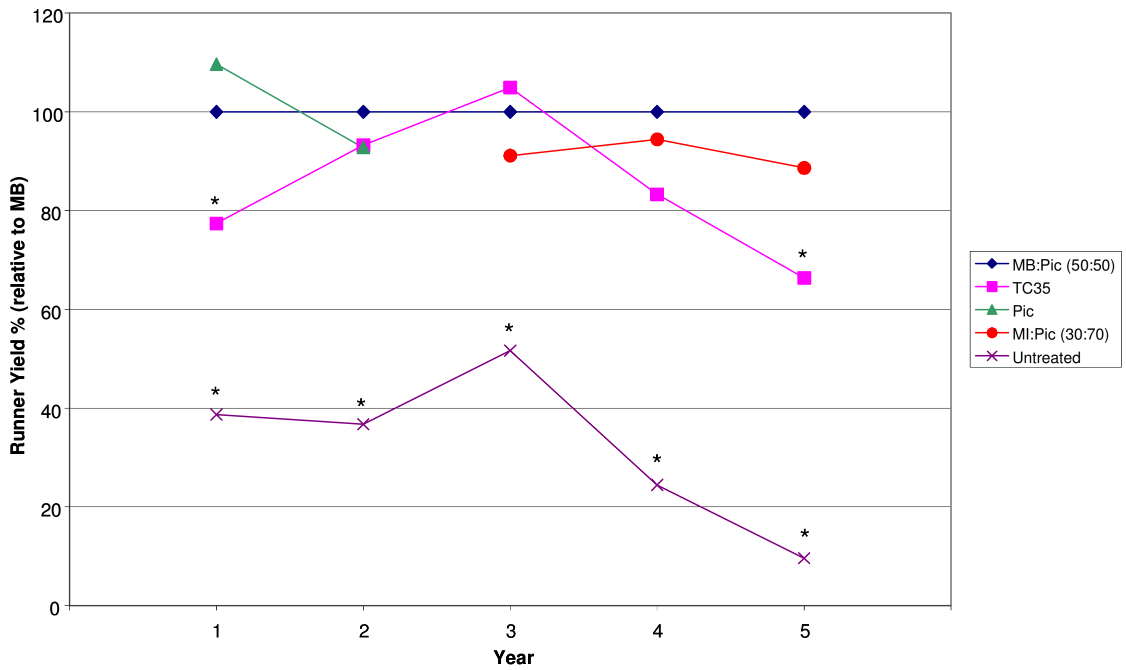


Figure 4.1. Relative yield (compared with yields in MB-treated soils) of strawberry runners grown in soils treated annually with alternative fumigants over five successive seasons. Runner yields in MB-treated plots ranged from 1.6-3.6 kg / linear metre. Data points marked with an asterisk are significantly different (where p = 0.05) from the MB control.

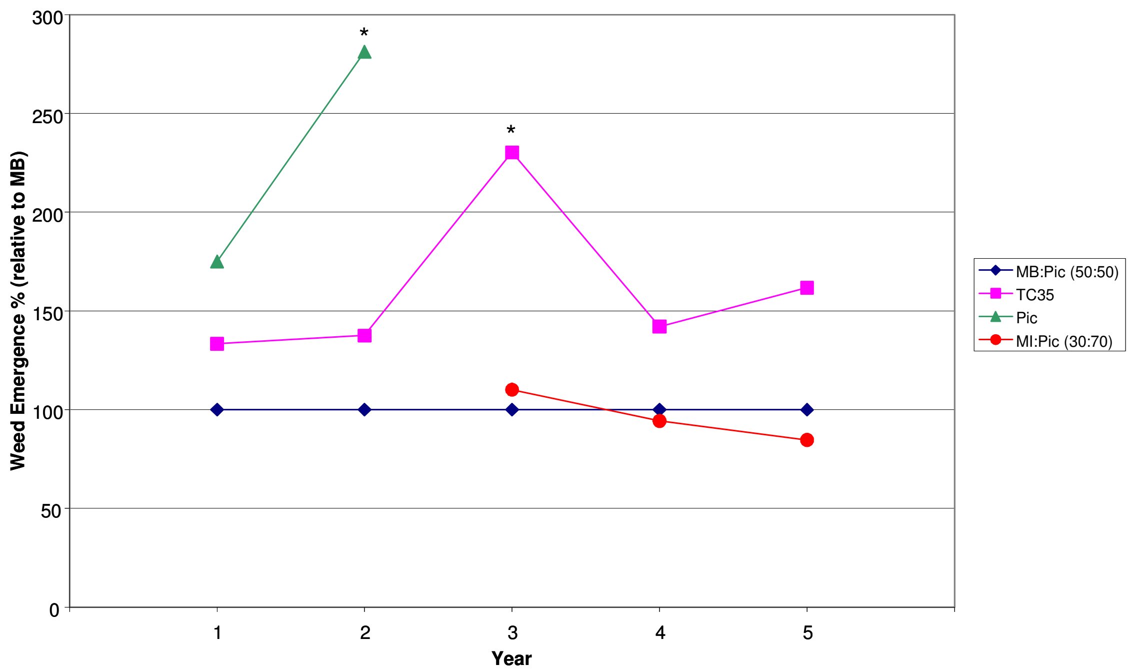


Figure 4.2. Relative weed emergence (compared with emergence in MB-treated soils) in soils treated annually with alternative fumigants over five successive seasons. Weed emergence in MB-treated plots ranged from 1.2 - 5.4 weeds / m². Data points marked with an asterisk are significantly different (where p = 0.05) from the MB control.

(compared with MB) residual times of Telone (1,3 dichloropropene) in soil - due to its higher boiling point (104°C) and lower vapour pressure (3.1 kPa) compared with MB (4°C, 190 kPa) and MI (43°C, 53 kPa), and the unique environmental conditions needed to grow strawberry runners (high altitudes with associated cold temperatures and high rainfall). The variable results with Telone C-35 suggest that it is currently an unsatisfactory risk for certified runner production, because similar yield losses in commercial plantings (as seen in this trial) could threaten the viability of the entire strawberry industry. However, it is important to note that Telone C-35 has delivered excellent results in all other Australian horticultural industries (eg strawberry fruit, melons, outdoor flowers, etc) where environmental conditions are better suited to its application. Moreover, Telone C35 has formed the backbone of most of Australian horticultural industries' strategies for replacing MB. Further research is required to test different formulations of Telone and chloropicrin that may be better suited to runner production (ie formulations with lower concentrations of Telone, such as Telone C-60) or better predictive tools to allow growers to detect residues of Telone C-35 in soil prior to planting (see Section 4.6).

Methyl iodide: Weed control and runner yields in plots treated with MI were statistically equivalent to those in MB-treated plots (Figs 4.1 & 4.2). The consistent yield results with MI suggest that it is has good potential as an alternative to MB for runner production, provided it is granted registration in Australia and is cost effective. Long-term trials with MI and other alternatives need to continue to ensure there are no adverse effects with the use of alternatives in the same soil over time (eg enhanced biodegradation, pathogen build up).

4.5 Integrated Weed Management (Toolangi, Vic; 2005)

Aim: (a) To investigate complimentary treatments such as herbicides and biofumigants to increase the weed control given by alternative fumigants. (b) To determine optimum application rates of MI for soil disinfestation and strawberry runner production.

Treatments:

Fumigants (Main-plots):
MB:Pic (70:30) (500 kg/ha)
Telone C-35 (500 kg/ha)
MI: Pic (30:70) (300, 400, and 500 kg/ha)
Untreated

IWM treatments (Split-plots):
Isoxaben (Gallery®) 135 g / ha
Isoxaben (Gallery®) 270 g / ha
Mustard oil (Voom®) (5 % solution) 50 mL / m^2
Mustard Meal (Fumafert®) 100 g / m^2
Untreated

Biofumigant treatments (mustard oil and mustard meal) were incorporated into soil with a rotary hoe and covered with LDPE barrier film for 7 days. Herbicide treatments (isoxaben) were applied directly over transplants and the surrounding soil after planting, using a motorised knapsack.

Design: Randomised split-plot design with 4 blocks

Variety: Gaviota (planted 7 weeks after fumigation, single row spaced 50 cm apart)

Assessments:

Weed establishment: Weed emergence was determined twice through the growing season (1 month after planting and 4 months after planting) as the number of individual species contained in five random 0.16 m^2 quadrats per plot.

Final yield: Final yields were determined 10 months after planting by digging and counting all runners contained within two random 0.5 m lengths of row per sub-plot.

Results:

Weed establishment:

Spergula arvensis (corn spurrey) and *Meliolotus* spp. (melilot) were the dominant emerging weeds on the site (54% and 25% abundance, respectively). All fumigants reduced total populations of emerging weeds compared with those in untreated plots (Table 4.1). Furthermore, MI (500 kg / ha and 300 kg / ha) controlled weeds better than MB, Telone C-35 or MI (400 kg / ha). Isoxaben controlled weeds to similar proportions as MB (compare Table 4.1 with 4.2), but biofumigants gave no significant weed control (Table 4. 2). There was no significant interaction between fumigant and IWM treatment for weed control.

Table 4.1. Average populations of emerging weeds in plots treated with various fumigants. Values followed by different letters in each column are significantly different, where p = 0.05.

Fumigant Treatment	Total Weeds / m^2
Untreated	326 a
MB:Pic - 70:30 (500 kg/ha)	47 b
MI:Pic - 30:70 (500 kg/ha)	17 c
MI:Pic - 30:70 (400 kg/ha)	33 b
MI:Pic - 30:70 (300 kg/ha)	22 c
Telone C-35 (500 kg/ha)	35 b

Table 4.2. Populations of emerging weeds in plots treated with various integrated weed management strategies (averaged across fumigant treatments). Values followed by different letters in each column are significantly different, where p = 0.05. There was no interaction between IWM and fumigant treatments.

IWM Treatment	Weeds / m^2
Untreated	25.5 a
Mustard Meal (100 g / m^2)	21.9 a
Mustard Oil (50 mL / m^2)	20.3 a
Isoxaben (135 g / ha)	14.3 b
Isoxaben (270 g / ha)	9.4 b

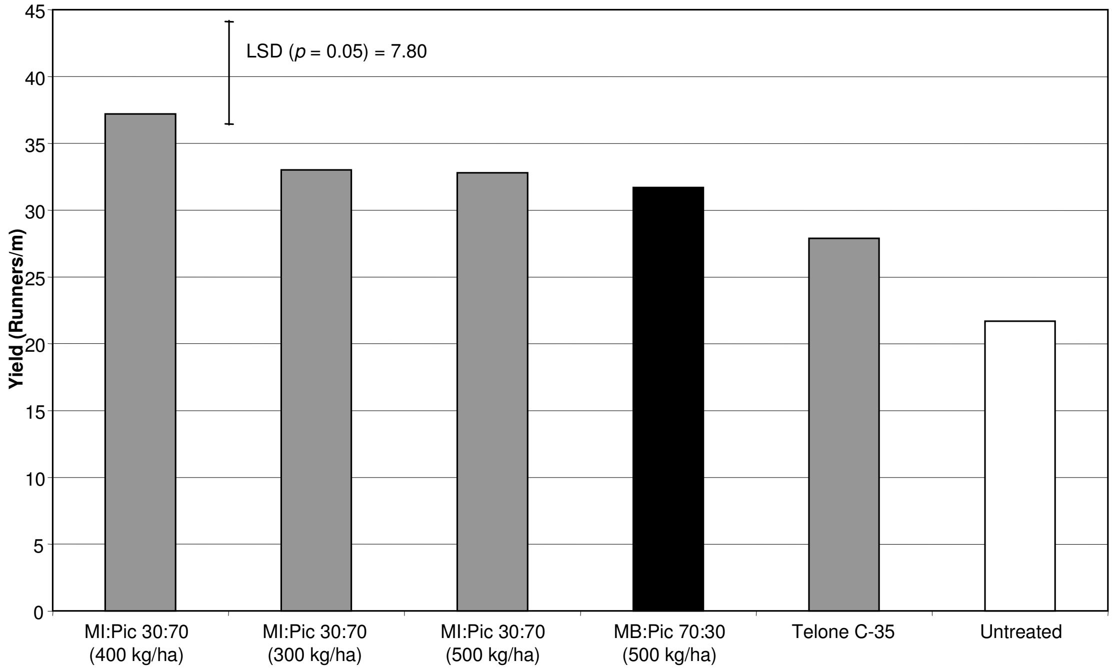


Figure 4.3. Final yields of strawberry runners grown in soils treated with various fumigants.

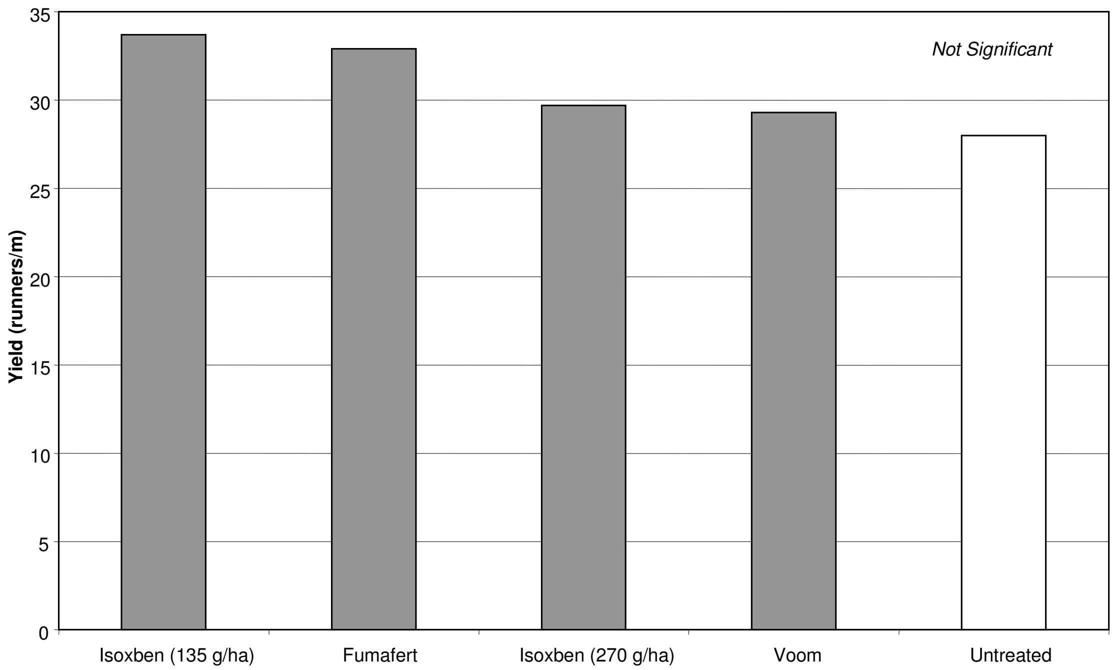


Figure 4. 4. Final yields of strawberry runners grown in soils treated with various integrated weed management treatments.

Final yield:

Soil disinfestation with all fumigants, except Telone C-35, increased runner yields by c. 50% compared with untreated plots (Fig 4.3). Soils treated with all alternative fumigants produced statistically equivalent runner yields to MB-treated plots. However, soils disinfested with MI:Pic (400 kg/ha) produced higher runner yields than those treated with Telone C-35. IWM treatments did not affect runner yields and there was no significant interaction between IWM and fumigant treatments (Fig 4.4).

Discussion:

This trial supports our previous work (BS01004, Section 4.4) in demonstrating the strong potential of MI as an alternative to MB for soil disinfestation and strawberry runner production. For example, MI reduced weed emergence to superior or equivalent levels as MB. Furthermore, final runner yields in MI-treated soils were equivalent to those in MB-treated soils, and greater than that in untreated soils.

There was no clear effect of application rate of MI in this trial. For example, MI applied at 300 kg/ha gave equivalent weed and pathogen control (Section 4.9) to MI applied at 500 kg/ha. MI applied at 400 kg/ha gave less weed control than either MI (300 kg/ha) or MI (500 kg/ha), and yet gave the greatest yield response. This may reflect the difficulties in consistently applying MI over these rate ranges. Therefore, the optimum application rate of MI for soil disinfestation and runner production in the Toolangi region appears to lie between 300-500 kg/ha. Further work is required to investigate different formulations of MI for soil disinfestation and runner production (eg MI:Pic 50:50), and to perform a cost benefit analysis on its application and use once registration is completed.

In the current trial, soil disinfestation with Telone C-35 did not increase final runner yields above those in untreated plots. This might relate to a sub-lethal incidence of fumigant phototoxicity, since Telone C-35 effectively controlled weeds and pathogens (Section 4.9) in this trial. Crop phototoxicity was not expected because fumigation occurred in summer under optimal environmental conditions, and a long plant-back time was observed (7 weeks). Clearly, more work is required to understand the edaphic and environmental factors that influence the retention of Telone C-35 and other fumigants in strawberry nursery soils.

In a study examining 17 different herbicides for controlling weeds in strawberry production, Fennimore & Richard (1999) demonstrated that isoxaben caused minimal crop damage and controlled 100% of *Trifolium* (clovers) and *Spergula* spp. (corn spurrey) weeds. For this reason they suggested that its use could be integrated with low rates of fumigants as an alternative to MB. The current trial supports these findings, as isoxaben reduced weed populations by 63% and caused no reduction in the growth or yields of strawberry runners. However, further trials are required to confirm that isoxaben causes minimal crop phytotoxicity in strawberries. In contrast, biofumigants provided no supplementary weed control in this trial, but reduced the viability of buried inoculum of strawberry pathogens by *c.* 15% (see Section 4.9).

4.6 Plant Back (Toolangi, Vic; 2006)

Aim: (a) To determine the plant-back times (the time needed between fumigation and planting to avoid phytotoxicity in crops) of alternative fumigants for strawberry runner production. (b) To evaluate support tools for allowing growers to predict when it is safe to plant runner crops after fumigation.

Treatments: *Fumigants (Main-plots):*
MB:Pic (50:50) (500 kg/ha)
Dazomet / Pic (separate applications* of 250 kg /ha each)
MI:Pic (30:70) (500 kg/ha)
MI:Pic (50:50) (500 kg/ha)
Telone C-35 (500 kg/ha)
Untreated

Plant-back treatments (Split-plots):
4 days after fumigation (96 hrs after fumigation)
1 week after fumigation (168 hrs after fumigation)
2 weeks after fumigation (336 hrs after fumigation)
4 weeks after fumigation (672 hrs after fumigation)
8 weeks after fumigation (1344 hrs after fumigation)

*Dazomet was incorporated into soil with a rotary hoe prior to applying chloropicrin.

Design: Randomised split-plot design with 4 blocks

Variety: Gaviota, single row spaced 50 cm apart

Assessments:
Lettuce test: An *in vitro* lettuce bioassay was conducted at each plant back time (96, 168, 336, 672 and 1344 hrs after fumigation). In this procedure, a 300 mL jar was half filled with soil from the plot and a moistened (2 mL of distilled water) cotton wool square with 20 lettuce seeds (var. Great Lakes) was placed in the jar on top of the soil. After 2 days, the percentage of germinating lettuce seeds (as visible to the naked eye) was determined. An inhibition of germination or a burning of roots in this test is a bio-indicator for the presence of fumigant residues in soils (BS98001), and may be used as a tool for growers to predict when it is safe to plant their crops.

Fumigant indicator tubes: The concentrations of MB, methyl isothiocyanate (in dazomet/Pic-treated plots), chloropicrin (in MI:Pic 30:70-treated plots), MI (in MI:Pic 50:50-treated plots), and 1,3 dichloropropene (in Telone C-35- treated plots) were determined at each plant back time using Gastec™ indicator tubes (as described in HG04018). Indicator tubes show a colour change in the presence of specific fumigants, and may also provide growers with a tool to predict when it is safe to plant their crops.

Final yield: Final yields were determined 12 months after planting by digging and counting all runners contained within two random 0.5 m lengths of row per sub-plot. Plant-back times for fumigants were determined based on final yields using the model described in project BS01004. Here, yields are expressed as a percentage of those in untreated plots (relative yield) to minimise the confounding factor of variable seasonal effects at the different plant-back times, and because untreated plots contain no fumigant residues and therefore form a reference yield. Additionally, relative yields are $\log_{10}$ transformed to restore homogeneity of variance across different plant-back treatments. The following exponential function is fitted to Log Relative Yield data for each fumigant:

$$Y_r = Y_m + B(S^P)\ldots\ldots\ldots\ldots(1)$$

where, Y_r is the Log Relative Yield; Y_m is the theoretical maximum Y_r attainable; B is a parameter defining Y_r when P = 0; S is the rate of increase of Y_r over P; and P is the plant-back time. The fitted function is used to calculate the required plant-back time for each fumigant (P_{opt}), under the conditions of the trial. P_{opt} is defined as the plant-back (P) where Y_r = 95%Y_m (Fig 4.5).

Results:

Overall, there was no significant difference in maximum runner yields (Ym) between any of the fumigant treatments, including the non-fumigated control (Fig 4.6). Figures 4.7 - 4.11 show: (a) fumigant concentrations in soil as determined by Gastec™ indicator tubes, (b) lettuce germination when exposed to fumigated soils, and (c) relative strawberry runner yields at different plant-back times for each fumigant. Overall, these parameters were well correlated (Figures 4.7- 4.11 (d)); with the lettuce test and fumigant indicator tubes providing a conservative estimate of plant-back times compared with runner yields (Table 4.3). This suggests that both tests have good potential for providing growers with an indication of when it is safe to plant their crops after fumigation (ie in addition to fumigant label recommendations as a minimum). However, paddock-scale sampling procedures would need to be developed before these tests could be adopted with any degree of confidence. Feedback from growers is that lettuce tests are cumbersome and difficult to undertake, and results are too slow. By comparison, indicator tubes are more expensive (c. $6-12 per sample), but are simple to use and provide instantaneous results.

Table 4.3. Predicted plant-back times for different fumigants applied in a trial at Toolangi, Vic using three methods. An exponential model described in the methods was used to predict plant-back from runner yields. Lettuce germination predicted plant-back when germination in fumigated soils was 95% of that in untreated soils. Indicator tubes predicted plant-back when fumigant concentrations in soil fell by 95% compared with initially applied rates and concentrations.

Fumigant	Runner Yield (P_{opt})	Lettuce Test	Fumigant Indicator Tubes
MB:Pic (50:50)	2.03 weeks	2.62 weeks	2.25 weeks
Daz/Pic	3.84 weeks	6.25 weeks	5.47 weeks
MI:Pic (30:70)	4.08 weeks	4.73 weeks	3.53 weeks
MI:Pic (50:50)	3.02 weeks	3.91 weeks	3.46 weeks
Telone C-35	1.95 weeks	4.67 weeks	4.54 weeks

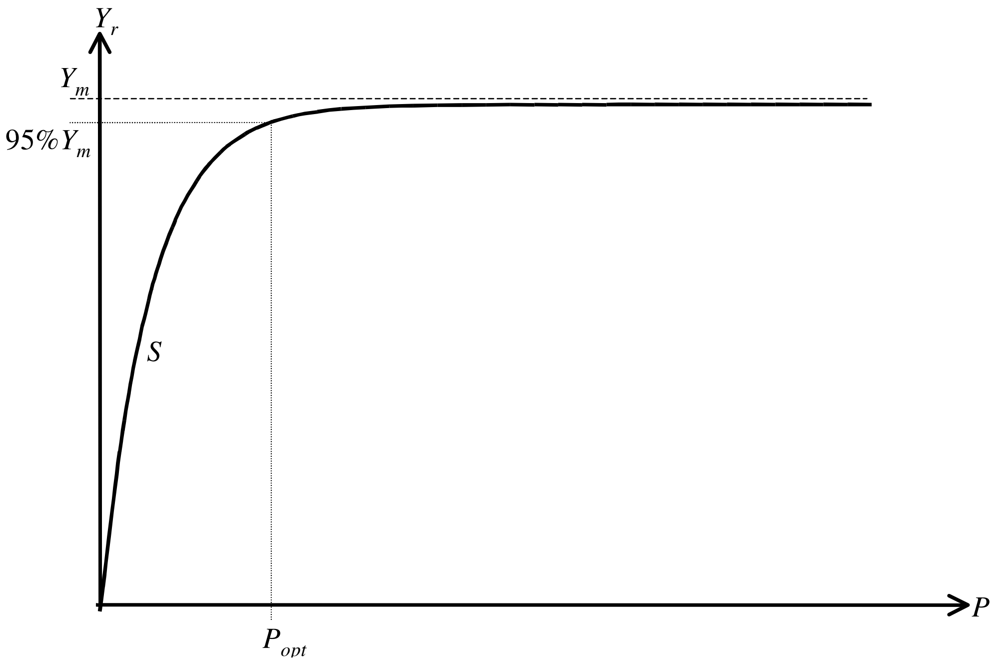


Figure 4.5. Exponential function (1) showing the relationship between Log10 Relative Yield (Y_r) and plant-back time (P). Y_m is the theoretical maximum Y_r attainable; and S is the rate of increase of Y_r over P. The required plant-back (P_{opt}) is defined as the P where Y_r = 95% Y_m.

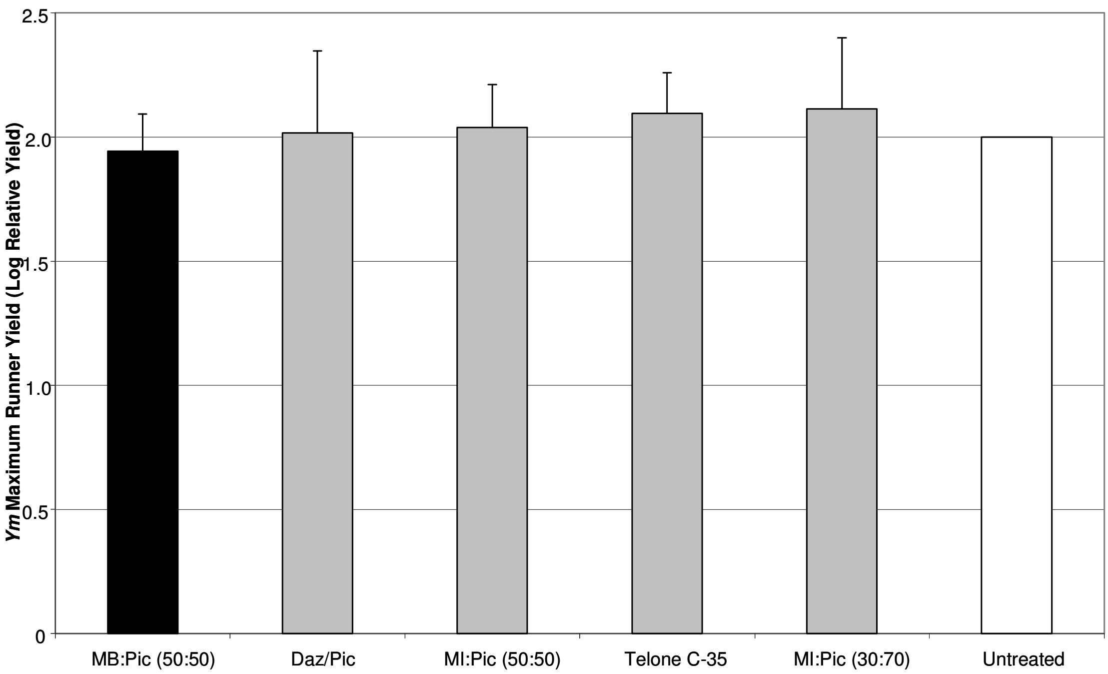
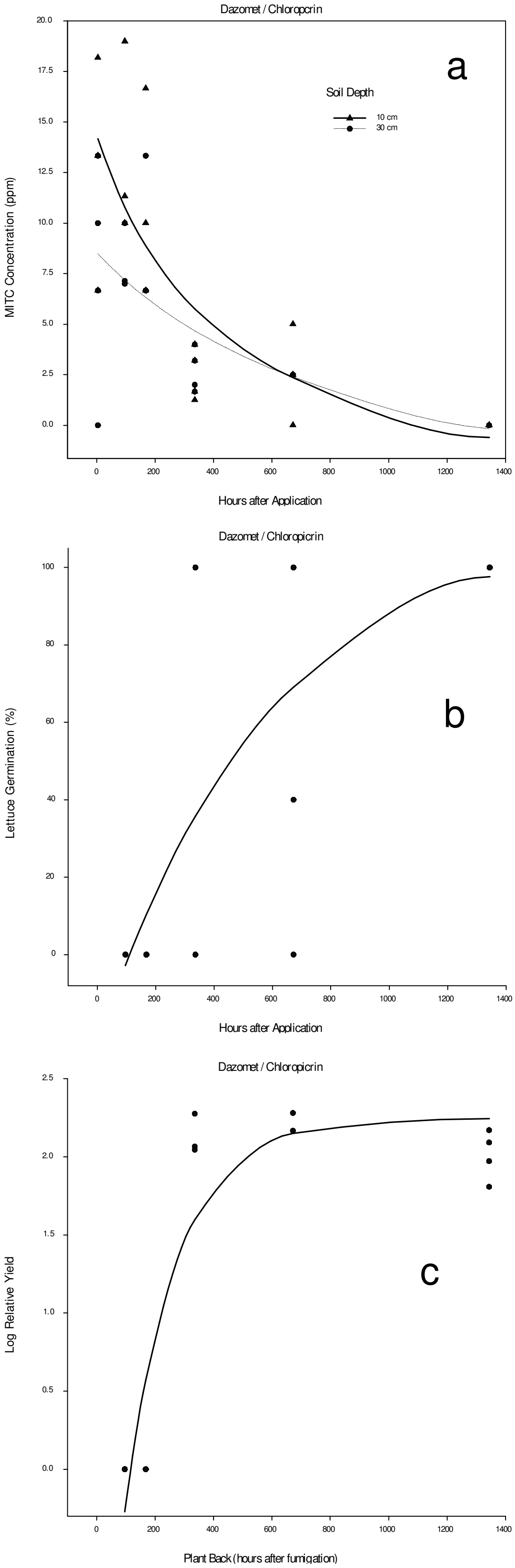


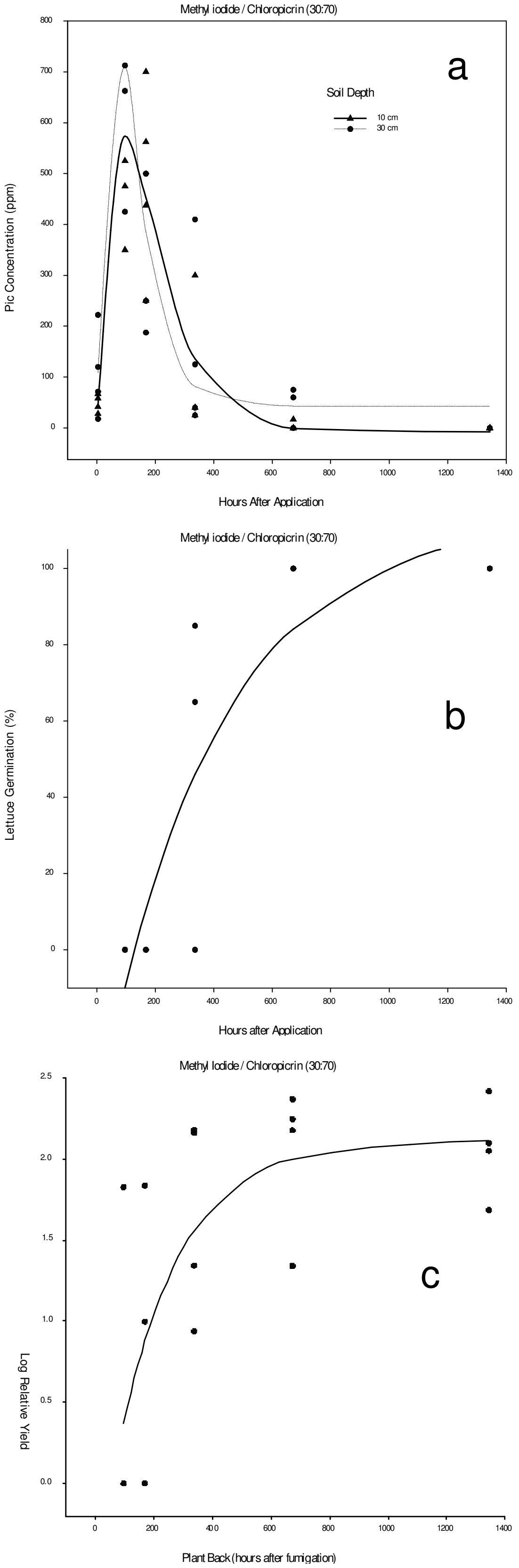
Figure 4.6. Maximum runner yields across different plant-back times in plots treated with various fumigants. Units are the $\log_{10}$ transformation of the relative (compared with yields in untreated plots) runner yield (%). Bars are standard errors where p = 0.05.



d

	Relative Yield	*Lettuce Germ.*	*MITC Conc.*
Relative Yield	1.00		
Lettuce Germ.	0.79	1.00	
MITC Conc.	-0.87	-0.97	1.00

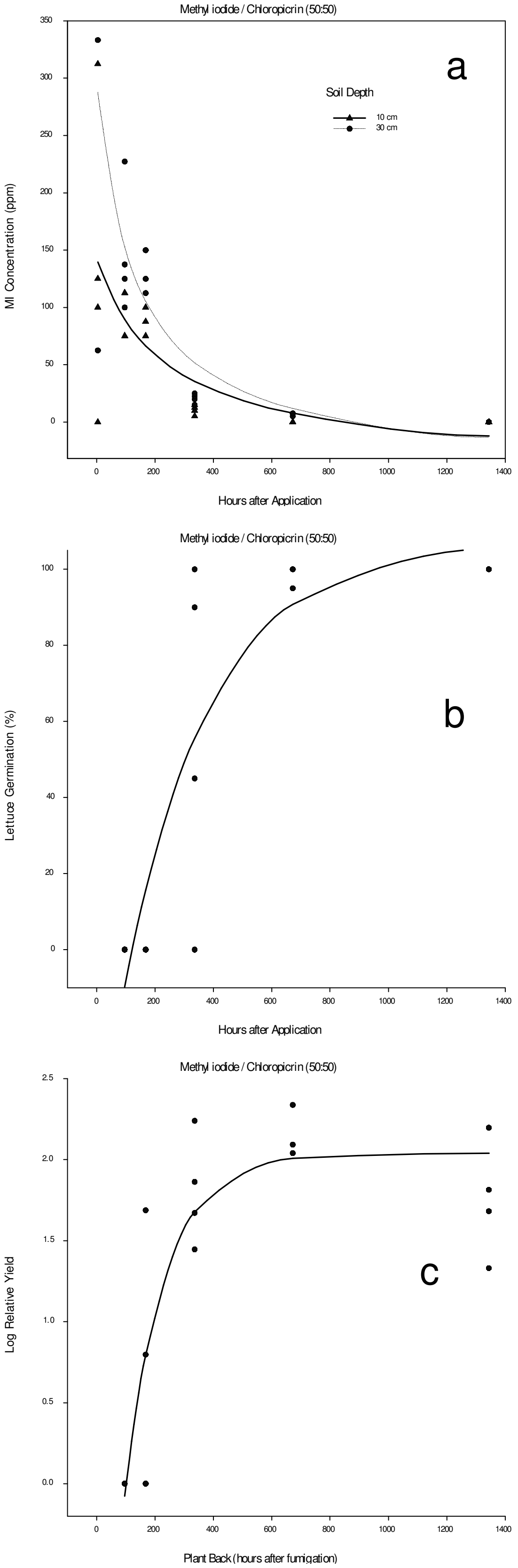
Figure 4.7.
(a) Concentration of methyl isothiocyanate (MITC) in soil over time in plots treated with the fumigant combination dazomet / chloropicrin. Concentrations were determined using Gastec fumigant indicator tubes. (b) Germination of lettuce seeds exposed to soils treated with the fumigant combination dazomet / chloropicrin. (c) Relative yields of strawberry runners (compared with yields in untreated soils) planted into soils treated with dazomet / chloropicrin after various intervals. (d) Correlations between relative strawberry yield, lettuce germination and MITC concentration in soils treated with dazomet / chloropicrin.



d

	Relative Yield	Lettuce Germ.	Pic Conc.
Relative Yield	1.00		
Lettuce Germ.	-0.93	1.00	
Pic Conc.	-0.94	0.96	1.00

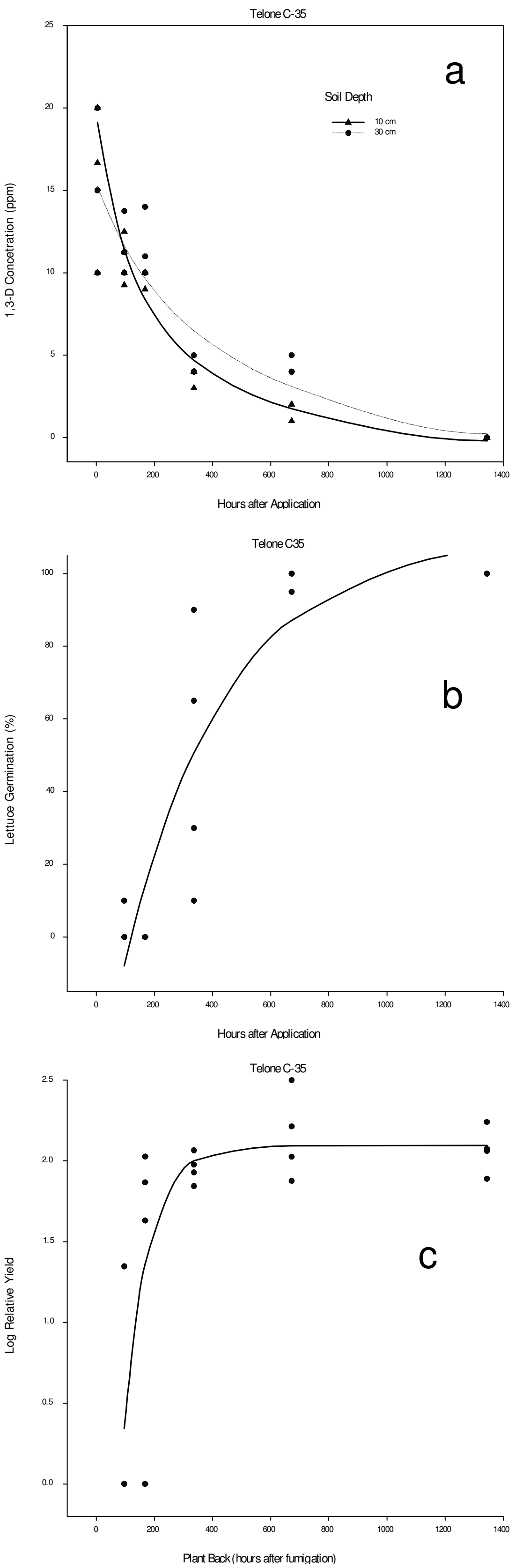
Figure 4.8.
(a) Concentration of chloropicrin (Pic) in soil over time in plots treated with the fumigant mixture methyl iodide / chloropicrin (30:70). Concentrations were determined using Gastec fumigant indicator tubes. (b) Germination of lettuce seeds exposed to soils treated with the fumigant mixture methyl iodide / chloropicrin (30:70). (c) Relative yields of strawberry runners (compared with yields in untreated soils) planted into soils treated with methyl iodide / chloropicrin (30:70) after various intervals. (d) Correlations between relative strawberry yield, lettuce germination and Pic concentration in soils treated with methyl iodide / chloropicrin (30:70).



d

	Relative Yield	*Lettuce Germ.*	*MI Conc.*
Relative Yield	1.00		
Lettuce Germ.	0.81	1.00	
MI Conc.	-0.77	-0.97	1.00

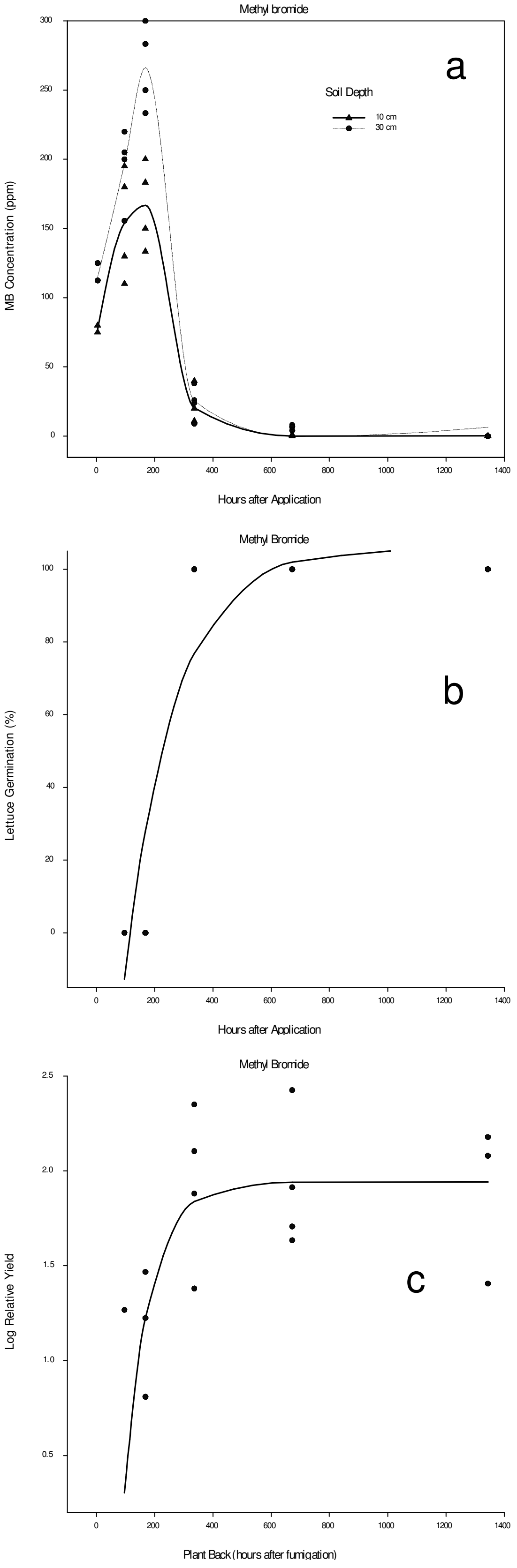
Figure 4.9.
(a) Concentration of methyl iodide (MI) in soil over time in plots treated with the fumigant mixture methyl iodide / chloropicrin (50:50). Concentrations were determined using Gastec fumigant indicator tubes. (b) Germination of lettuce seeds exposed to soils treated with the fumigant mixture methyl iodide / chloropicrin (50:50). (c) Relative yields of strawberry runners (compared with yields in untreated soils) planted into soils treated with methyl iodide / chloropicrin (50:50) after various intervals. (d) Correlations between relative strawberry yield, lettuce germination and MI concentration in soils treated with methyl iodide / chloropicrin (50:50).



d

	Relative Yield	*Lettuce Germ.*	*1,3-D conc.*
Relative Yield	1.00		
Lettuce Germ.	0.91	1.00	
1,3-D Conc.	-0.84	-0.93	1.00

Figure 4.10.
(a) Concentration of 1,3 dichloropropene (1,3-D) in soil over time in plots treated with the fumigant combination 1,3-D / chloropicrin (65:35) (Telone C-35). Concentrations were determined using Gastec fumigant indicator tubes. (b) Germination of lettuce seeds exposed to soils treated with the fumigant Telone C-35. (c) Relative yields of strawberry runners (compared with yields in untreated soils) planted into soils treated with Telone C-35 after various intervals. (d) Correlations between relative strawberry yield, lettuce germination and 1,3-D concentration in soils treated with Telone C-35.



d

	Relative Yield	*Lettuce Germ.*	*MB Conc.*
Relative Yield	1.00		
Lettuce Germ.	0.99	1.00	
MB Conc.	-0.98	-1.00	1.00

Figure 4.11.
(a) Concentration of methyl bromide (MB) in soil over time in plots treated with the fumigant mixture methyl bromide / chloropicrin (50:50). Concentrations were determined using Gastec fumigant indicator tubes. (b) Germination of lettuce seeds exposed to soils treated with the fumigant mixture methyl bromide / chloropicrin. (c) Relative yields of strawberry runners (compared with yields in untreated soils) planted into soils treated with methyl bromide / chloropicrin (50:50) after various intervals. (d) Correlations between relative strawberry yield, lettuce germination and MB concentration in soils treated with methyl bromide / chloropicrin.

The plant-back time for Telone C-35 in this trial (1.95 weeks) was markedly shorter than in previous plant-back trials (6.79 – 12.96 weeks) conducted in the runner industry (BS01004). Moreover, even after plant-back periods as long as 3 months, fumigation of soils with Telone C-35 has occasionally caused yield losses in the runner industry of more than 30% due to fumigant-induced phytotoxicity (Section 4.4 and BS01004). This is in contrast to trial results in other Australian horticultural industries where plant-back times for Telone C-35 have been short, and yield responses high (eg up to 30% yield increase in strawberry fruit compared with soils treated with MB, BS98001). Currently, the high variability in plant-back times and yield responses in the strawberry runner industry with Telone C-35 represent an unacceptable risk for its adoption as a MB replacement. More controlled studies are needed to understand the interaction of environmental and edaphic effects on Telone C-35 degradation and dissipation in the heavy clay soils in the Toolangi region (particularly under cold temperatures and high moisture contents).

Plant back times for MI:Pic 50:50 in this trial were shorter than for the 30:70 formulation. This is expected because the residual time of chloropicrin in soil is longer than methyl iodide – due to differences in boiling point (Pic: 112°C, MI: 43°C) and vapour pressure (Pic: 2.25 kPa, MI: 53 kPa) between the two fumigants.

4.7 Plug Plants (Toolangi, Vic; Wanneroo, WA; and Main Ridge, Vic; 2005-2006)

Aim: To determine the fruit yielding potential of strawberry plug plants (containerised transplants produced in soil-less media), and their potential to offset the production of bare-rooted runners in MB-fumigated soils.

Treatments:

Varieties:
Diamante
Camarosa
Gaviota

Conditioning (8 days):
4°C, 8 hours day-length
4°C, 12 hours day-length
20°C, 8 hours day-length
20°C, 12 hours day-length

Plant-material:
Bare-tips
Plugged tips
Bare-rooted runners produced in MB-treated soil (control)

Design: Randomised complete design with 4 block

Method:
Strawberry runner tips were produced in a table-top hydroponics system at Toolangi, Vic (Fig 4.12). Harvested tips were either: (1) conditioned for 8 days (see treatments above) in a controlled environment room, plugged into transplant containers containing soil-less media, misted, and hardened off outside; or (2) plugged into transplant trays containing soil-less media, misted, conditioned for 8 days in a controlled environment room (Fig 4.13), and hardened off outside. The petiole lengths of the primary leaf of ten random transplants per treatment were measured following hardening off. Two strawberry fruit trials were conducted with the plug plants - one in a sandy soil fumigated with Telone C-35 (500 kg/ha) at Wanneroo WA, and the second in a clay loam soil fumigated with MB:Pic 30:70 (500 kg/ha) at Main Ridge Vic. Traditional bare-rooted runners (produced in MB-treated soil) of each variety were included in the trials as the control. Strawberry growth and fruit yields were taken throughout the growing season.

Results / Discussion:
Following hardening off, transplants that were conditioned as plugs generally had longer petioles than those conditioned as tips (Fig 4.14). Diamante and Camarosa tips conditioned at 20°C had particularly short petioles and appeared stunted compared with other transplants (Fig 4.14). Despite this, all plug transplants established vigorously in fruit trials irrespective of conditioning treatment - producing double the leaf numbers of bare-rooted runners (Fig 4.15). In the WA trial, the yield responses of plug plants varied by variety. For Gaviota and Camarosa, fruit yields of plug plants were c. 60% and 30% (respectively) above those of bare-rooted runners by the end of the season (Fig 4.15). Despite this, bare-rooted runners yielded 30% more than plug plants for Diamante (Fig 4.15). There were no consistent differences in the fruit yields of plug plants conditioned under different treatments. In the Victorian trial, there were no significant differences between treatments (including between plug plants and bare-rooted runners) for any variety.

The production of plug transplants utilises hydroponics and soil-less technologies and therefore offers runner growers an alternative system to the production of bare-rooted runners in MB-treated soils. Research (eg Durner et al., 2002) and adoption patterns overseas show that some strawberry fruit production regions (eg North Carolina) are more suited to the use of plug plants than others (eg California). Moreover, the physiology of plug plants and the environments needed to condition them for fruit and runner production are poorly understood. Plug plants are up to 5 times more expensive to produce than bare-rooted runners (Mattner et al., 2003), and therefore must consistently produce higher or earlier fruit yields than bare-rooted runners to be cost effective. The current trial demonstrates that there is potential to develop specific strawberry varieties as plug plants, but more research is required to understand their conditioning and physiology before they can provide fruit growers with consistently high yields.

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Figure 4.12. Table-top hydroponics system used to produce strawberry runner tips.

Figure 4.13. Plugged strawberry runner tips undergoing a conditioning treatment in a controlled environment room.

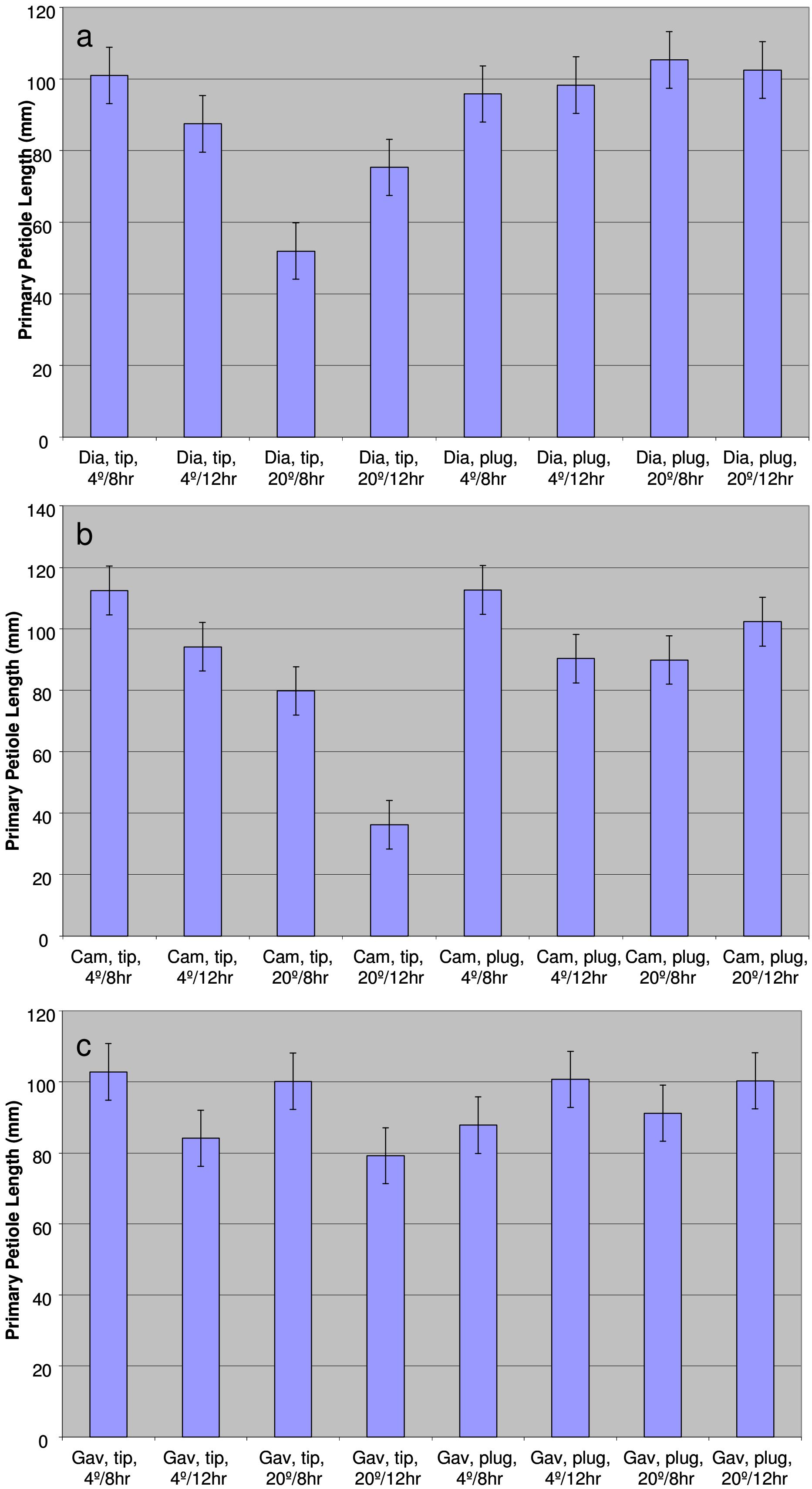


Figure 4.14. Petiole lengths of (a) Diamante, (b) Camarosa, and (c) Gaviota strawberry transplants (following hardening off and prior to planting) exposed to different conditioning treatments. Bars are the LSD where p = 0.05.

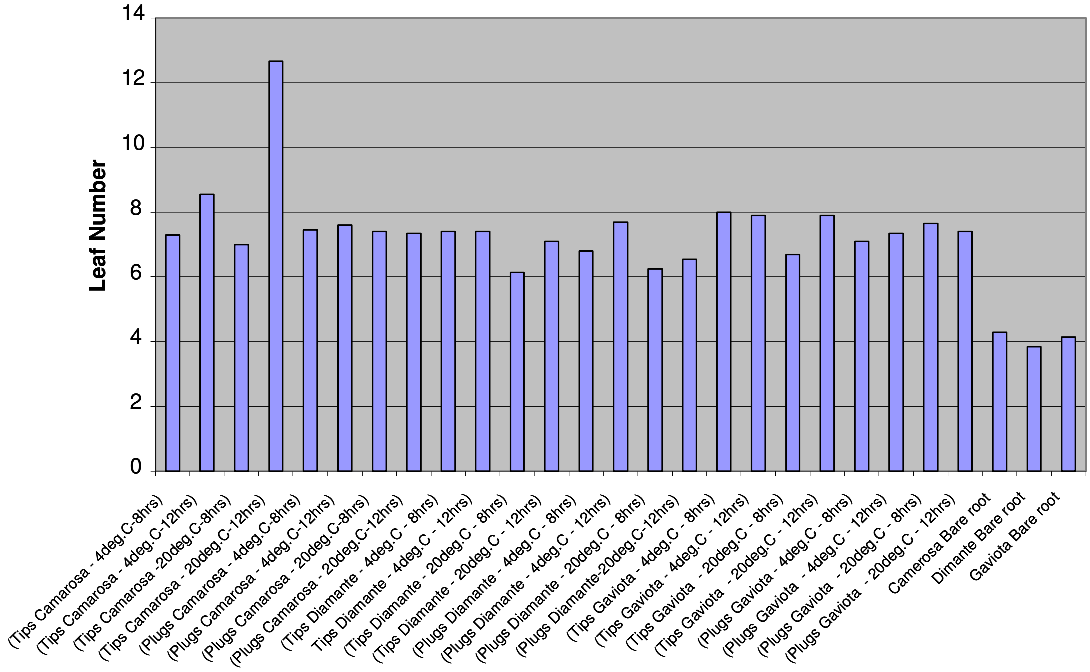


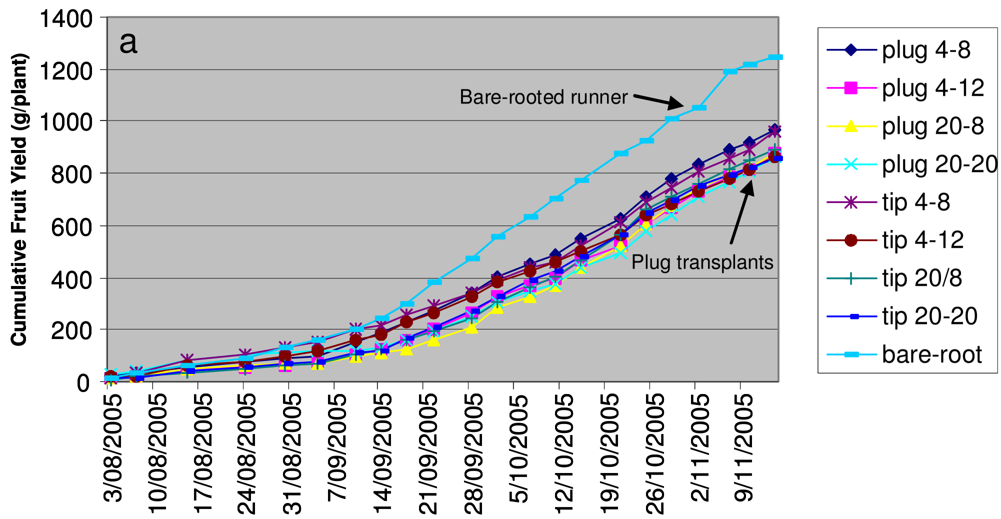
Figure 4.15. Leaf numbers of strawberry plants (one month after planting) grown from conditioned plug plants or bare-rooted runners in a strawberry fruit trial at Main Ridge, Victoria.

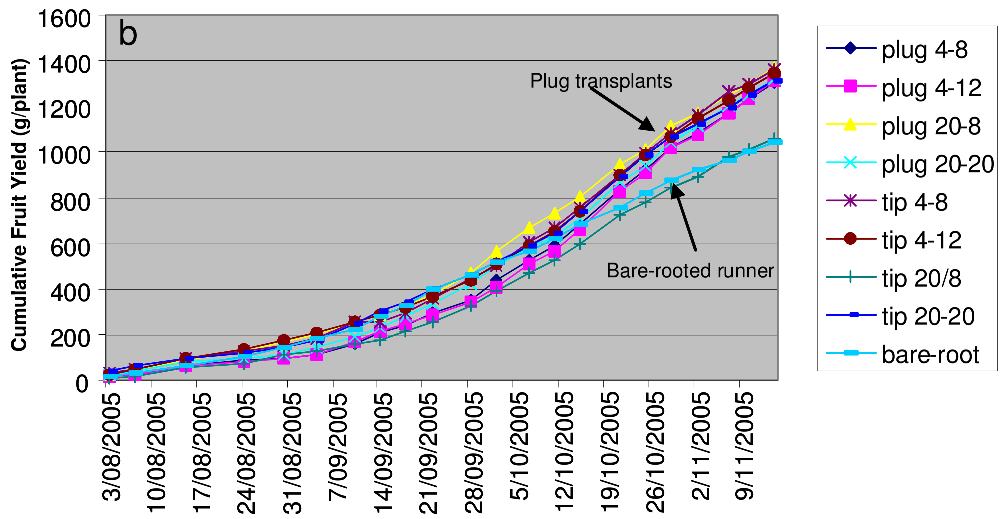
4.8 Micro-Propagation (Toolangi and Millgrove, Vic 2006-2008)

Aim: To determine the potential for micro-propagated and plug transplants to offset the need for MB in the foundation and mother stock generations of strawberry runner production.

Treatments:	*Mother Stock Transplants:* Bare-rooted runners produced in MB-treated soil Plug transplants produced in soil-less media Micro-propagated plantlets produced in growth media
Design:	Randomised complete design with 4 blocks
Variety:	Albion, single row spaced 100 cm apart

Method: Micro-propagated (tissue culture) and plug plant mother stock were produced using commercial-in confidence procedures. Bare-rooted mother stock were produced in MB-fumigated soils (MB:Pic 50:50, 500 kg/ha) using standard industry procedures. The three different forms of mother stock were then planted into MB-fumigated runner beds (MB:Pic 50:50, 500 kg/ha), and growth and development monitored through the normal growing season. Ten months after planting, runners in all plots were dug and counted.





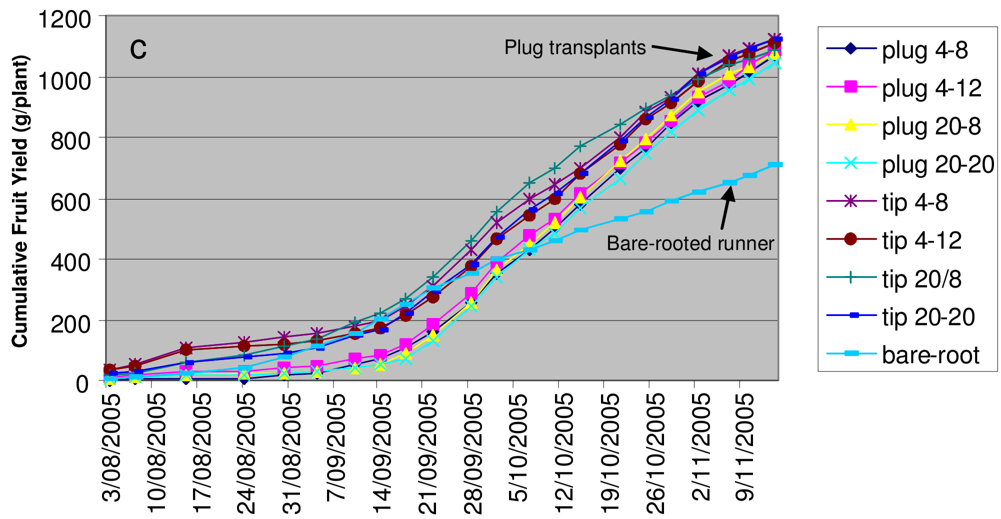


Figure 4.15. Fruit yields of (a) Diamante, (b) Camarosa and (c) Gaviota strawberry plants grown from conditioned plug transplants or bare-rooted runners in a trial at Wanneroo Western Australia.

Results / Discussion:

Strawberry runner yields from micro-propagated mother stock were 25% higher than those from traditional bare-rooted stock (Fig 4.16). The higher runner yield from micro-propagated stock concurs with previous research (Zebrowska et al., 2003) and is expected due to the presence of 6-benzyladenine in the tissue culture medium, which enhances axillary bud activity. Micro-propagated plants have the potential to replace runners grown in MB-treated soils for foundation and/or mother plant production (c. 0.5-1.5 tonne of MB pa). Furthermore, it could reduce the amount of land needed to grow strawberry runners proportionate to the yield increases it induces, thereby potentially offsetting the need for a further 7 tonnes of MB pa in the runner industry. However, there is uncertainty over whether runner plants from micro-propagated mother stock remain true-to-type, and if their fruiting quality and yields are maintained compared with traditionally produced runners. To address these issues, runners harvested from the different mother stock types in this trial were collected and are currently being trialled in the strawberry fruit industry. These results will be reported in an upcoming HAL project (BS07014). Also, a full cost analysis of micro-propagation systems is required before adoption of these technologies could be considered by industry.

In contrast to micro-propagated transplants, runner yields from plug plant mother stock were 25% below those from bare rooted stock (Fig 4.16). As with plug plants for fruiting stock (Section 4.7), a greater understanding of the physiology of plug plants is required before they could be considered as a replacement for bare-rooted mother stock produced in MB-fumigated soils.

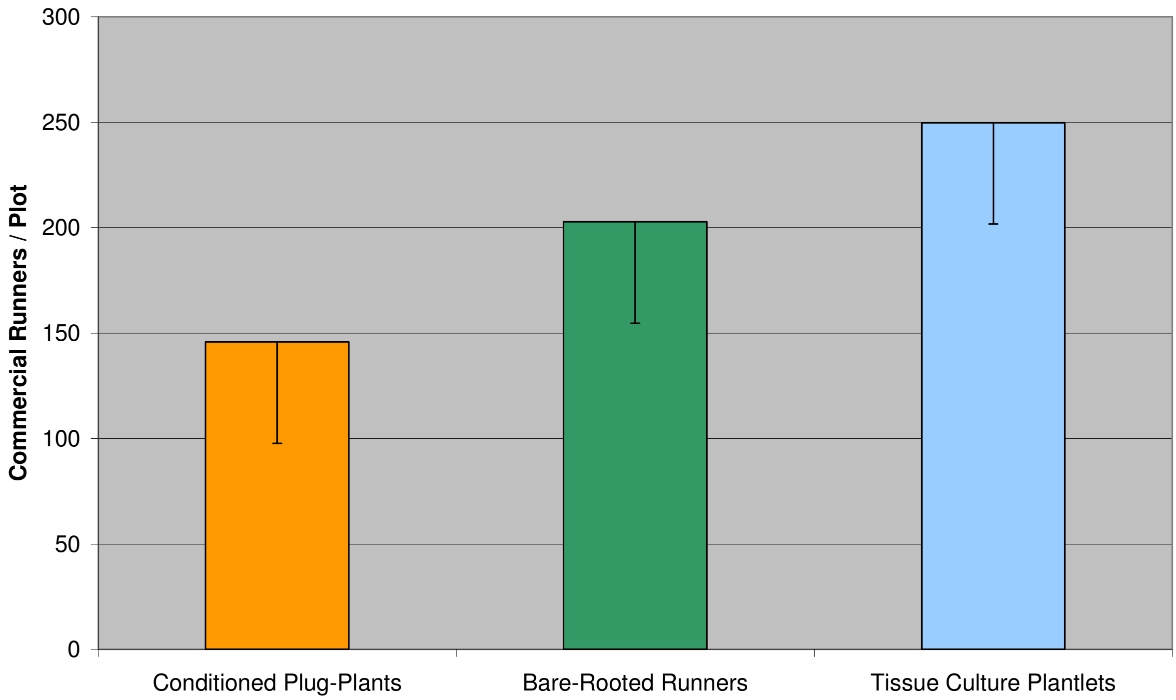


Figure 4.16. Runner yields from mother stock produced using different technologies. Bars are the LSD where p = 0.05.

4.9 Pathogen Control (Toolangi, Vic 2005-2007)

Aim: To investigate the relative efficacy of MB alternatives for controlling fungal pathogens of strawberry.

Methods: Experiments to compare the relative efficacy of MB alternatives for controlling fungal pathogens of strawberries were conducted in the previously described trials. In these experiments, muslin bags containing 1g of inoculum of various pathogens (*Rhizoctonia fragariae*, causal agent of black root rot; *Sclerotium rolfsii*, causal agent of Sclerotium wilt; *Verticillium dahliae*, causal agent of Verticillium wilt) were buried in soil, immediately after fumigation, at selected bed positions (ie relative to the tyne) and depths (10cm, 20cm, 30cm). Inoculum of *R. fragariae* was grown on double autoclaved (121°C, 20 min) millet seed and inoculum of *S. rolfsii* and *V. dahliae* consisted of sclerotia and microsclerotia, respectively. Inoculum was recovered 5 days after fumigation and its viability determined by plating at least 10 pieces onto agar media (PDA+A).

Results:

Long-term fumigant use (Section 4.4):

In all seasons investigations were conducted, all fumigants (MB:Pic 50:50; Telone C-35 and MI:Pic 30:70) reduced the viability of inoculum of *R. fragariae*, *S. rolfsii*, and *V. dahliae* from between 95-100% to nil.

Integrated weed management (Section 4.5):

MB and low rates of MI (300 kg/ha) were the only fumigants that consistently killed inoculum of *R. fragariae* and *S. rolfsii* in the trial (Table 4.4). However, higher rates of MI (400 & 500 kg/ha) gave statistically equivalent control of both pathogens to MB. Telone C-35 killed inoculum of *R. fragariae*, but gave significantly lower levels of control of *S. rolfsii* than MB and MI. Biofumigant treatments (mustard meal and mustard oil) reduced the inoculum viability of both pathogens, but only to small degrees (c. 15%). Mustard meal reduced the viability of pathogens significantly more than mustard oil.

Table 4.4. Viability of buried inoculum of the strawberry pathogens *Rhizoctonia fragariae* and *Sclerotium rolfsii* following soil disinfestation with various treatments in a strawberry runner trial at Toolangi, Victoria. Values followed by different letters in each column are significantly different, where p = 0.05.

Fumigant Treatment	Viability of Inoculum (%)	
	Rhizoctonia fragariae	*Sclerotium rolfsii*
Untreated	78.7 d	88.0 d
MB:Pic 70:30 (500 kg/ha)	0.0 a	0.0 a
MI:Pic 30:70 (500 kg/ha)	0.0 a	2.5 a
MI:Pic 30:70 (400 kg/ha)	3.4 a	5.0 a
MI:Pic 30:70 (300 kg/ha)	0.0 a	0.0 a
Telone C-35 (500 kg/ha	0.0 a	14.7 b
Mustard Meal (100 g/m^2)	59.2 b	73.4 c

Mustard Oil (50 mL/ m^2)	70.1 c	77.2 cd

Plant-back (Section 4.6):

All fumigants controlled *R. fragariae* to equivalent levels as MB. Similarly, all fumigants except Telone C-35 controlled *V. dahliae* to equivalent levels as MB (Table 4.5).

Table 4.5. Viability (%) of buried inoculum of the strawberry pathogens *Rhizoctonia fragariae* and *Verticillium dahliae* following soil disinfestation with various treatments in a strawberry runner trial at Toolangi, Victoria. Values followed by difference letters in each column are significantly different, where p = 0.05.

	Viability %	
	R.fragariae	***V.dahliae***
Untreated	100.0 a	95.0 a
MB:Pic 50:50 (500 kg/ha)	7.5 b	0.0 c
MI:Pic 30:70 (500 kg/ha)	5.0 b	0.0 c
MI:Pic 50:50 (500 kg/ha)	7.5 b	5.0 bc
Telone C35 (500 kg/ha)	10.0 b	7.5 b
Daz/Pic (250+250 kg/ha)	2.5 b	0.0 c

Discussion:

Information on the ability of fumigants to control pathogens is vital for the strawberry runner industry, so that certification standards can be maintained following MB phase-out. Previous to these experiments, there was little information on the comparative abilities of alternative fumigants for controlling soil-borne pathogens of strawberries in Australia. This was due to trials on MB alternatives mostly being conducted on individual growers' properties, which had low disease pressures (BS98001). Introducing artificial inoculum into soils is one method of addressing this lack of information, although the relevance of data generated by this technique may not directly apply to field situations of natural pathogen infestations.

Trends in results showed that alternative fumigants containing high concentrations of chloropicrin (ie MI:Pic 30:70 and MI:Pic 50:50) controlled pathogens better than those with lower concentrations (ie Telone C35 (1,3-D:Pic 65:35). This trend was expected because chloropicrin is a more powerful fungicide than MB and other alternative fumigants (Desmacheliar, 1998). The effect was most pronounced for sclerote forming pathogens (*S. rolfsii* and *V. dahliae*), which have a protective rind that may act as a partial barrier to fumigant penetration of the organism. The efficacy of Telone C-35 against pathogens might be improved by increasing the proportion of chloropicrin in the formulation (eg Telone C-60). Future research aims to evaluate the efficacy of fumigants against natural populations of soil-borne pathogens using molecular techniques (q PCR).

4.10 Grower trials (Toolangi, Millgrove, Wandin, Coldstream, Vic; 2005-06)

A series of five participatory, grower trials were conducted in the strawberry fruit and runner industries with alternative fumigants. These trials aimed to increase growers' confidence and experience in using alternatives. The trials typically consisted of large, randomised blocks fumigated with Telone C-35, chloropicrin, MI:Pic (30:70), and MB:Pic (50:50 or 30:70). The size and number of trials was limited by experimental permit conditions, and because growers needed to discard fruit produced in soils treated with non-registered products. Industry workshops were held at the sites of the participatory trials, and host growers were able to discuss their experiences with using the alternatives. One such event attracted 30% of the Victorian strawberry fruit industry (65 growers) and was important factor in allowing the industry to transition to alternative fumigants. Generally, results from trials showed that disease and weed control, and yields with alternative fumigants were equivalent or better to that with MB (Table 4.6; Fig 4.17).

Table 4.6. Runner yields in a grower trial at Toolangi, Vic.

Fumigant	**Runner Yield** (No. of plants / linear m)
MI:Pic 30:70 (500 kg/ha)	135.1
MB:Pic 50:50 (500 kg/ha)	155.6

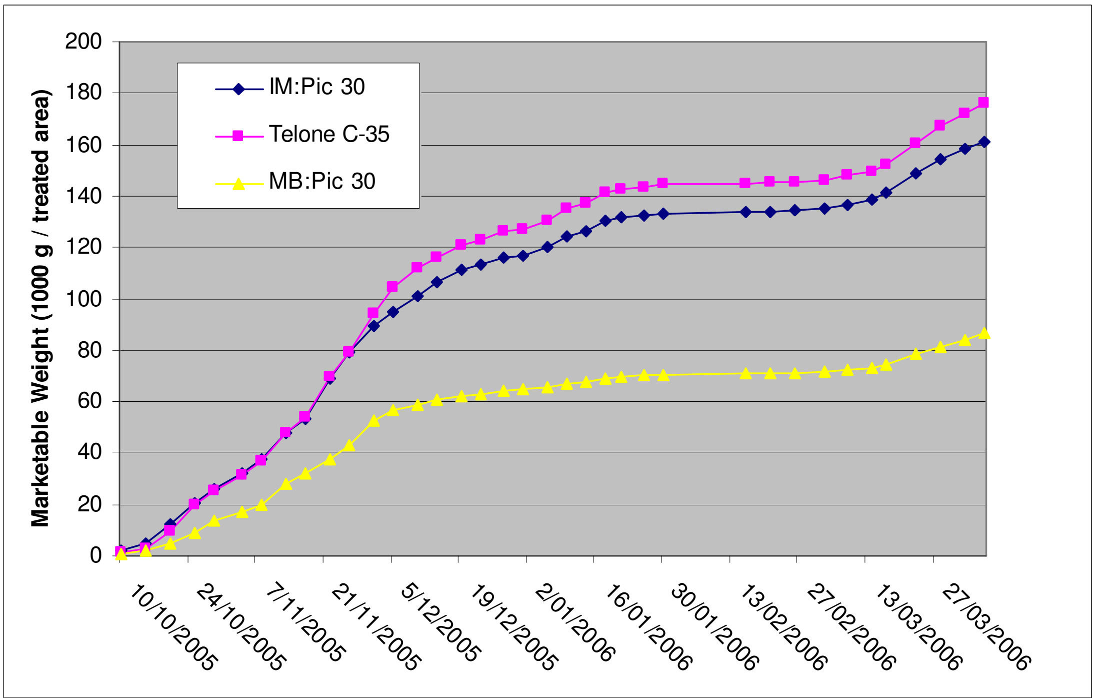


Figure 4.17. Fruit yields in a grower trial investigating three fumigants (MI:Pic 30:70, 500 kg/ha; Telone C-35, 500 kg/ha; and MB:Pic 30:70, 500 kg/ha) at Coldstream Vic.

5 Methyl bromide alternatives: New Zealand research trials

5.1 Summary

A series of strawberry fruit trials conducted in New Zealand have demonstrated the increased importance, compared with methyl bromide, of applying alternative fumigants under optimal soil and environmental conditions. In wet/compacted soils, residence times of some alternative fumigants were long (> 35 days for Telone C-35) and their distribution through the soil profile was uneven. These conditions probably caused reduced efficacy and poor yields with some alternatives, compared with MB, in individual trials. These differences relate to the higher boiling points and lower vapour pressures of alternative fumigants (eg metam sodium (MITC) boiling point = 119°C and vapour pressure = 2.62 kPa) compared with MB (boiling point = 4°C and vapour pressure = 190 kPa). However, when alternative fumigants were applied under optimal soil and environmental conditions they were as efficacious at controlling pathogens and weeds, and produced equal strawberry yields to MB. For these reasons, growers need to carefully follow label recommendations with regards to environmental conditions at application, plant-back times, and rates when using alternative fumigants. Separate studies showed that impermeable films have the capacity to retain fumigant residues for longer periods in soil than standard polyethylene films, and therefore may allow reduced application rates of fumigants in the strawberry industry. Unlike the strawberry runner industry where barrier films are removed soon after treatment (see Chapter 6), there are no off-gassing issues with the use of impermeable films in the fruit industry because they are retained on the soil for the full cropping cycle.

Key findings averaged across different strawberry varieties were:

- Methyl bromide, methyl iodide and chloropicrin (in 'good' soil conditions only) gave similar fruit yields.
- Telone C35 and chloropicrin (in wet soil conditions, 'poor' soil) averaged 10 to 15% lower yields than MB.
- Metham sodim (Fumasol) yielded 24% and 59% less fruit than MB in 'good and 'poor' soil, respectively .
- Untreated, urea, compost and biofumigant (mustard oil) treatments yielded 40-60% less fruit than MB.
- Root health and overall plant health were generally best in MB, chloropicrin, methyl iodide, and Telone C35 treatments. Health of plants in the metham sodium treatment was inferior to that under the other fumigants.
- Responses differed for different strawberry varieties.
- If soil conditions were 'poor' at fumigation, fruit yields in some treatments were lower than with fumigation in 'good' soil. This was particularly noticeable in the metham sodium and chloropicrin treatments, but was not a factor with MB or methyl iodide. Telone C35 gave differing results for the different varieties.
- None of the potential biological controls (various *Trichoderma*-based products and compost tea) tested in sub-plots gave any improvement over the untreated control.

- Studies of pathogen kill and destruction of weed seeds showed that all the tested fumigants gave good control of both pathogens and weeds, but other treatments had minimal effect. Counts of weeds in early spring showed a similar response.

5.2 Introduction

In Australia and New Zealand, strawberry fruit growers have been reluctant to adopt alternatives to methyl bromide, mainly because of a lack of confidence in the effectiveness of the alternative products. This is in spite of a number of trials showing only small differences in performance in most years. Part of the concern is the purported inferior performance of alternative products where soil conditions are not ideal during preparation and fumigation, or where abnormally wet seasons follow fumigation with slightly weaker products. To date, most trials have been conducted in soils that have been in good condition. In addition to these issues, Australian strawberry fruit growers have lacked confidence in alternative fumigants because of a scarcity of data demonstrating efficacy against natural populations of pathogens.

Fumigation trials were established in 2005 and 2006 on HortResearch's Roselea Experimental Garden in Havelock North, New Zealand. This site is a silt/clay loam (similar soil texture to fruit growing regions in New Zealand and Australia), and has grown strawberries for most of the previous eight years. The site has also been deliberately infested with the strawberry pathogens *Phytophthora cactorum* and *Verticillium* spp., to give high background disease pressure and allow rigorous testing of soil treatment products. It is the only site in the southern hemisphere with such high manipulated populations of strawberry pathogens, and therefore was the ideal location to conduct collaborative trans-Tasman strawberry trials with alternative fumigants. The 2005 and 2006 trials had primary aims of:

1. assessing the relative performance of a number of potential fumigant replacements for methyl bromide
2. assess the potential of a number of non-fumigant alternatives
3. determining the effectiveness of alternative fumigants in sub-optimal soil conditions during ground preparation and fumigation
4. determining the effectiveness of alternative fumigants where abnormally wet conditions exist during plant growth and cropping
5. determining the effectiveness of alternative fumigants under high disease pressures

5.2 Roselea trial 2005

In April 2005, an extensive soil treatment trial was established in the Roselea Research Garden in Havelock North (Figure 5.1).

A range of chemical fumigants (methyl bromide/chloropicrin 50:50 (*MeBr/C*); chloropicrin (*Chloro*); Telone®C35 [1,3-dichloropropene/chloropicrin 65:35] (*TelC35*); Fumasol™[metham sodium] (*Fum*); methyl iodide/chloropicrin 50:50 (*Iodomethane*)) plus 'softer' treatments

(Voom® (mustard oil); urea; compost; untreated control) were applied in replicated plots. Additional plots of plants treated with potential biological control or other additives were included by imbedding these within some of the treatment beds (untreated control, Fumasol, compost, mustard oil). Products applied were Agrimm Trichoflow™, Grochem DRH Trichoderma, compost tea, urea, and untreated. The aim was to see whether some of these treatment combinations have any beneficial effect on plant performance.

Super-imposed on this, as split plots, was a study of soil conditions during ground preparation and fumigation. To achieve this, some plots were over-irrigated prior to ground preparation and fumigation, then ground was cultivated and beds formed across the 'wet' and 'dry' sub-plots. Gravimetric soil water content was approximately 29% in dry plots and 35.5% in wet plots prior to cultivation and bed formation. At 29% water content, the Roselea soil was in good condition for cultivation and fumigation. At 35% water content, this soil is normally considered too wet for cultivation and fumigation. Subsequent soil analyses in June, two months after fumigation and bed formation, showed that soil preparation and fumigation in soil that was too wet did indeed have a detrimental effect on soil structure. Soil MWD (mean weight diameter or aggregate size) was 9.93 in good soil and 19.35 in wet soil. This indicates that soil preparation in wet conditions resulted in a much 'cloddier' seed bed to an extent that might be expected to impact on fumigation response.

In the main plots (both in wet and dry ends), three different strawberry varieties were planted ('Pajaro', 'Camarosa' and 'Gaviota'). The biological control and plant-back sub-plots had only 'Pajaro'. In all, there were 730 planted plots in the trial.

Figure 5.1. Main trial at Roselea, May 2005.

Plant back time

The extended wait time after fumigation before planting (plant-back time) is potentially one of the main problems with some of the alternative fumigants. As another dimension in the Roselea trial, plant-back time was investigated in all treatments. 'Pajaro' strawberry plants were planted 1, 2, 3 and 4 weeks after fumigation and bed formation. The main planting was five weeks after fumigation. Main trends showed that plant losses were high in chloropicrin, methyl iodide, methyl bromide and TeloneC35 plots when planted one week after gassing. By two weeks, differences between treatments were difficult to determine. Because of extremely hot and dry conditions during the early and mid-April plantings, however, plant losses were high, confounding interpretation of results.

Weed kill

Weed seeds (ryegrass and clover) and shoots (couch grass and mallow) were buried in mesh bags in the top 5 cm in fumigated plots. One week after fumigation, bags were retrieved and attempts made to germinate the seeds and grow the shoots in potting mix. Most seeds were killed in the fumigant plots, compared with 94 to 100% survival in all other treatments (Table 5.1). Results for the couch grass and mallow shoot survival showed a similar trend to that of the ryegrass and clover seeds.

Table 5.1. Weed seed germination and shoot survival following burial in mesh bags during soil treatment with various products.

	Seed Germination %		Shoot survival %
	Ryegrass	Clover	Couch grass
1. untreated	96	100	77.5
2. methyl bromide	0	0	0
3. Telone®C35	0	3	0
4. chloropicrin	0	0	0
5. Methyl iodide	0	0	0
6. Fumasol™	0	4	5
7. mustard oil	94	100	72.5
8. urea	96	100	77.5
9. compost	98	100	82.5

In September, all plots were weeded and weed data was collected. Weed numbers were relatively low in all fumigated plots, but substantially higher in untreated, urea, and compost treatments (Figure 5.2). Mustard oil treatments gave intermediate weed numbers, suggesting a slight (though not statistically significant) reduction in weed germination with this treatment.

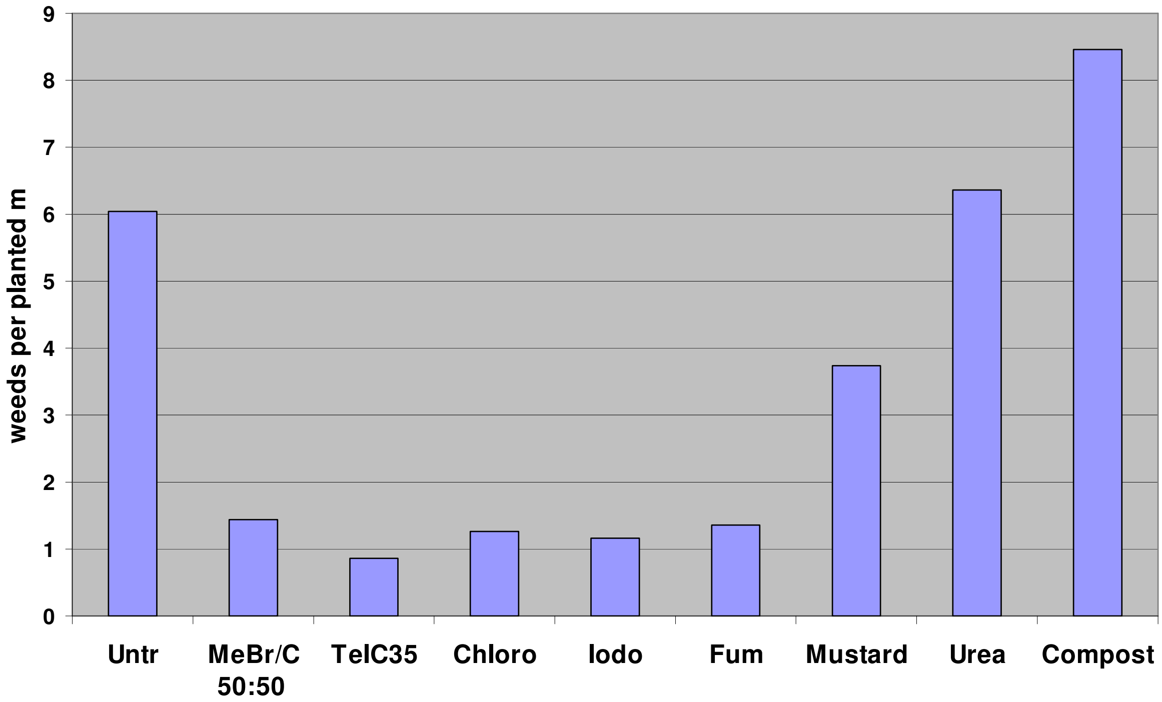


Figure 5.2. Weeds growing in Main Roselea trial fruiting beds, September 2005. Data are average numbers of weeds per 6-m plot.

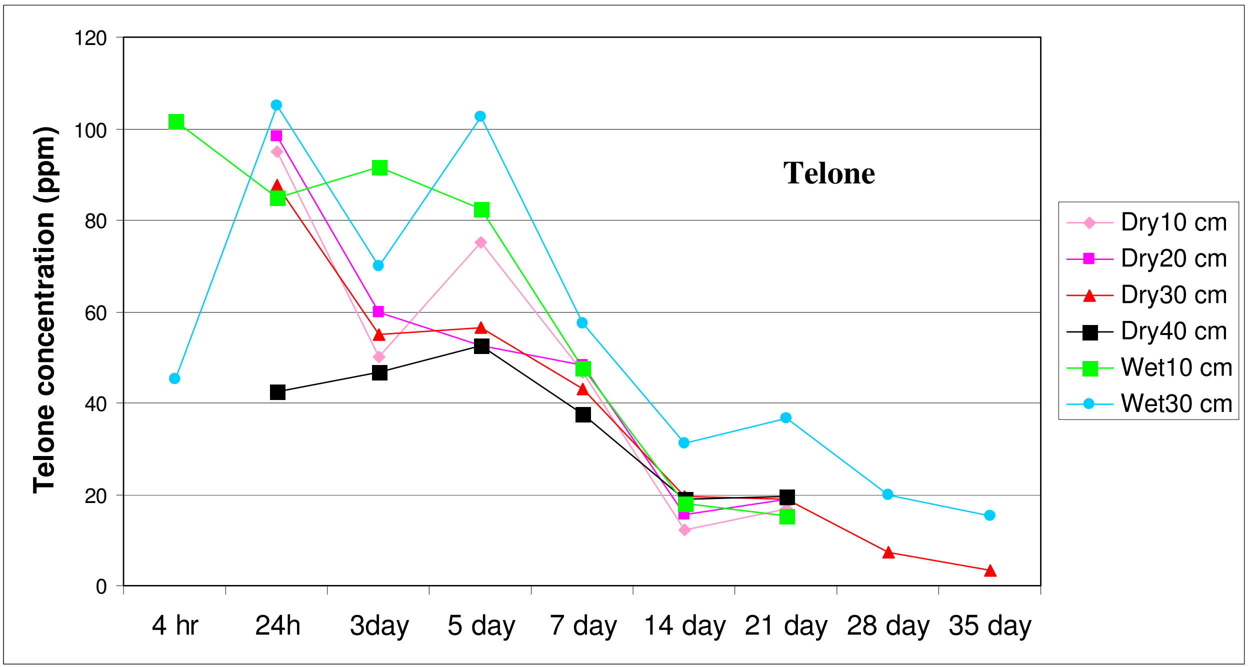
Pathogen kill

Within three hours of fumigation, 6x6 cm mesh bags containing fungal inoculum (Phytophthora cactorum and *Verticillium dahliae*) were buried at depths of 10, 20, 30 and 40 cm. These were removed two weeks after fumigation, and assayed for fungal survival. Results showed a 95 to 100% kill of *Phytophthora* and *Verticillium* down to 40 cm in all of the fumigant treatments (methyl bromide, chloropicrin, Telone C35, Iodomethane) except Fumasol, which was effective down to 30 cm. None of the other treatments had any measurable effect on *Phytophthora* survival.

Gas movement in soil

Some of the alternative fumigants move slowly through the soil, potentially limiting their effectiveness. Associated with this poor movement, some products may also remain in the soil long after fumigation, potentially delaying planting or causing phytotoxicity problems. In the 2005 season, two fumigants (Telone C35 and methyl iodide) were chosen for analysis to study their movement through soil following application. Immediately following fumigation, gas sample tubes were inserted into the fumigated beds at depths of 10, 20, 30 and 40 cm. At intervals of 4 h, 24 h, 3, 5, 7, 14, 21, 28 and 35 days, gas samples were extracted and analysed using Gastec tubes (Gastec Inc., Japan). A summary of results is presented in Figure 5.3.

The two gases behaved very differently in soil. Within four hours of application, methyl iodide had moved well through the soil profile, even in wet soil, and was at high concentration at least down to 30 cm. Readings after 24 h showed that in both wet and dry soil, methyl iodide was evenly distributed throughout the soil profile at least down to 40 cm (Figure 5.3). Over the first week, gas concentrations in the soil declined rapidly, and were negligible by day 14. In contrast, Telone did not move as well as methyl iodide. After 4 h, the gas concentration was high at 10 cm depth, but lower at 30 cm, indicating that the gas hadn't moved through the profile as quickly. After 24 h, the gas had moved well down to 30 cm, but was still at a lower concentration at 40 cm. The decline of gas concentration in the soil was also much slower for Telone. After seven days, gas concentrations were still high throughout the soil profile, with moderate levels still remaining after three weeks. In wet soil, particularly at depth, gas concentrations remained high for longer. In wet soil at 30 cm depth, gas concentrations were still at 15 ppm after five weeks.



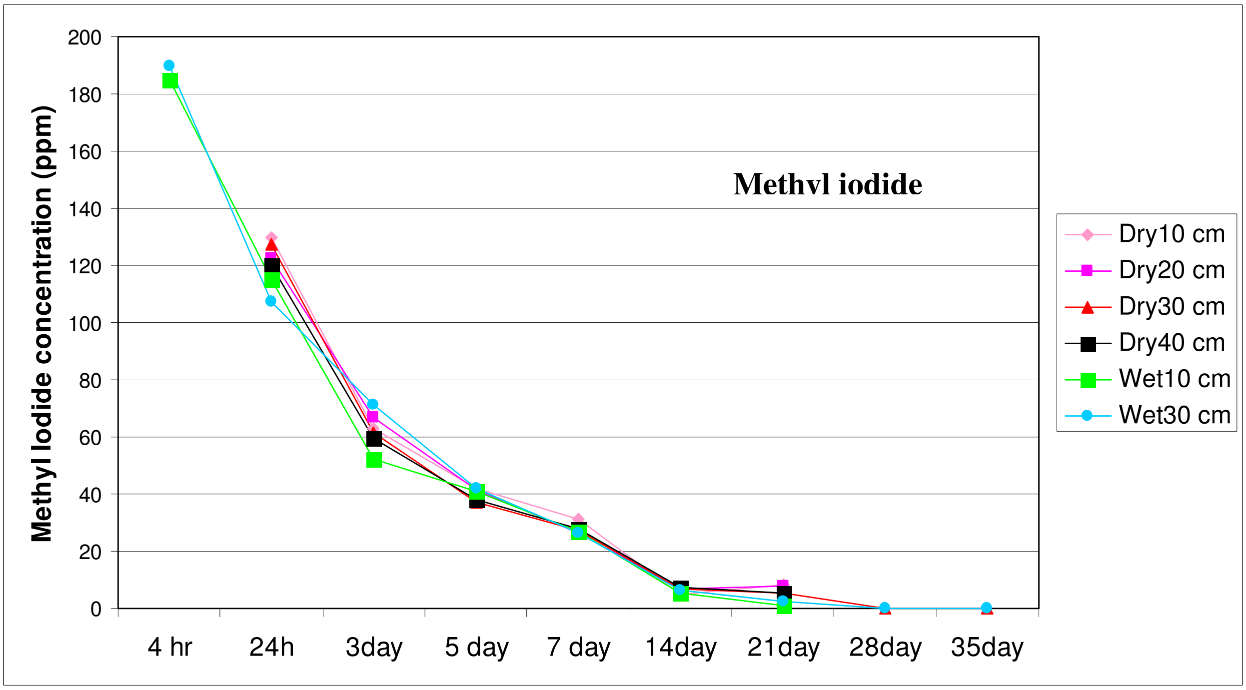


Figure 5.3. Concentration of Telone and methyl iodide in the soil air at various depths and time intervals following fumigation. Both wet (poor) and dry (good) soil conditions were sampled.

These data show that in terms of gas penetration and subsequent release from the soil, methyl iodide is potentially a superior fumigant to Telone. Methyl iodide moves quickly and evenly throughout the soil profile, and then disappears rapidly from the soil. On the other hand, Telone is slower to move through the soil profile, and it remains in the soil for much longer, particularly in wet soil. This could lead to problems with phytotoxicity if planting is too soon after fumigation, particularly in sub-optimal soil conditions.

Plant growth, disease and crop assessments

Plant vigour and health was assessed prior to the first harvest, and again at the end of the harvest season. The final assessment included excavation of plants and determination of root health. Plant canopy health data averaged across both wet and dry plots are presented in Figure 5.4, and full results of plant height, health, and root health are summarised in Appendix 5.1.

Fruit from all plots was harvested and weighed throughout the main fruiting season. Total yield data are presented in Figure 5.5.

Results were similar for all three varieties. Plant height, fruit weight, canopy health and root health were generally significantly better in methyl bromide, methyl iodide, chloropicrin and Telone C35 plots than in the untreated control. Methyl bromide was the best performer of this top group for all parameters measured, and Telone C35 was generally the poorest. Differences within this top group of four, however, were never statistically significant (see Appendix 5.1).

The bottom group of treatments included the untreated control, urea, mustard oil (Voom) and compost. Of this group, the untreated control was the poorest performer for most parameters and compost was generally the best. Fumasol was generally mid-way between the top group of fumigants and the lower non-fumigant treatments. Overall, the performance of Fumasol was poorer than expected, well behind the main group of fumigants. The various biological control treatments applied (Trichoderma products and compost tea) gave plant growth, health and fruit yield results very similar to the untreated control (data not presented), and were deemed ineffective.

Effects of soil condition on plant performance

The interactions between soil condition during ground preparation/fumigation (good=dry vs. poor=wet) and the various treatments, varieties and assessments made are complex and difficult to interpret. A summary of data is given in Appendix 5.2. Fruit yield data (Figure 5.6) indicates that for most treatments, yield in dry plots was approximately equal or slightly higher than in wet plots, although there are some exceptions to this generalisation.

Fumasol was the treatment that seemed most detrimentally affected by the wet soil conditions. For all varieties and for all parameters measured, performance of Fumasol was lower in poor (wet) soil compared to good (dry) soil (Appendix 5.2). In good conditions, performance of Fumasol was not far behind that of the other fumigants, but in wet conditions it was clearly inferior.

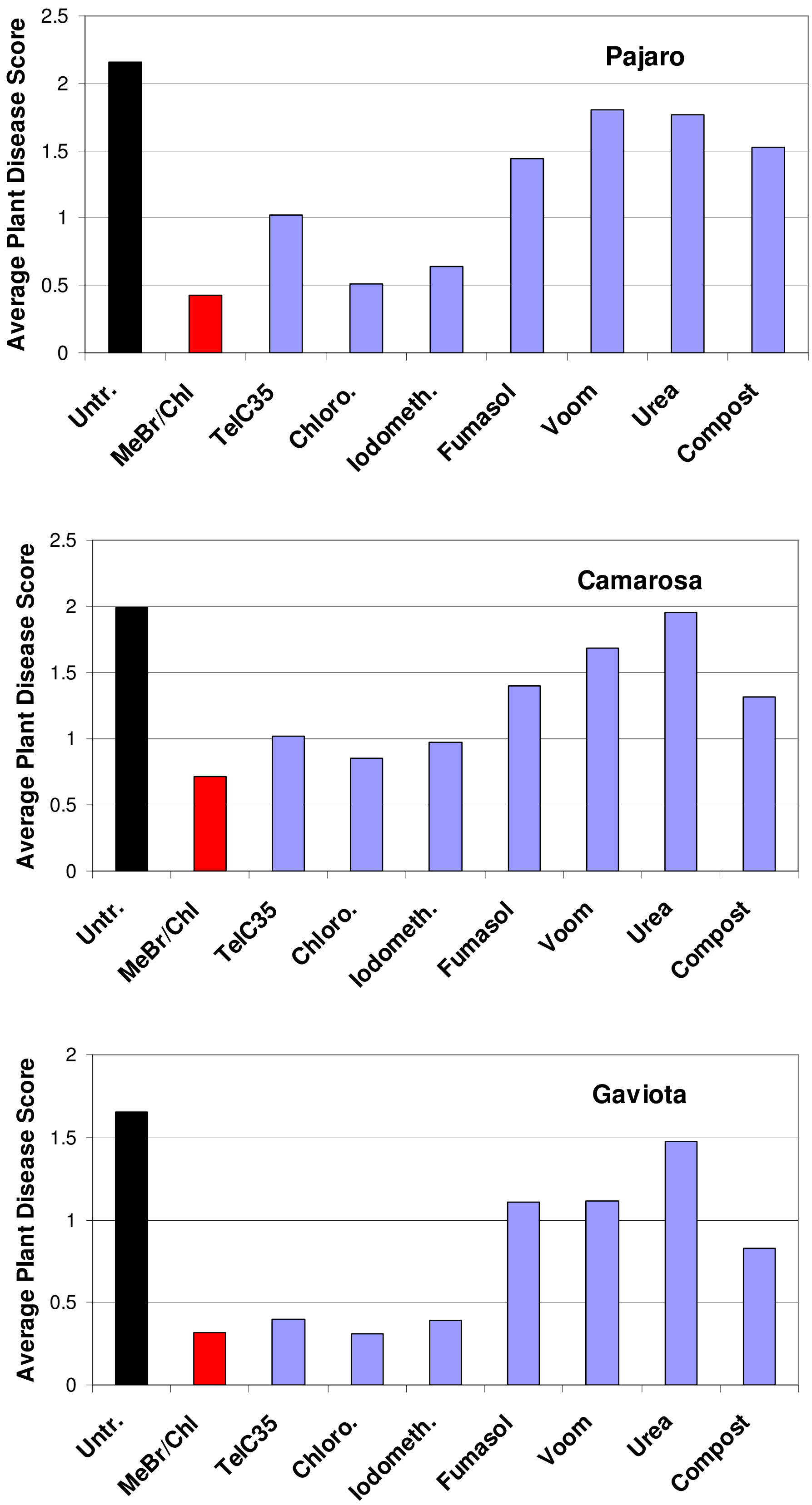


Figure 5.4. Final plant disease assessments, Main Roselea trial, January 2006. Plant health was scored on a 0 to 4 scale where 0 was healthy and 4 was dead. Data are combined means of both dry and wet plots for each variety.

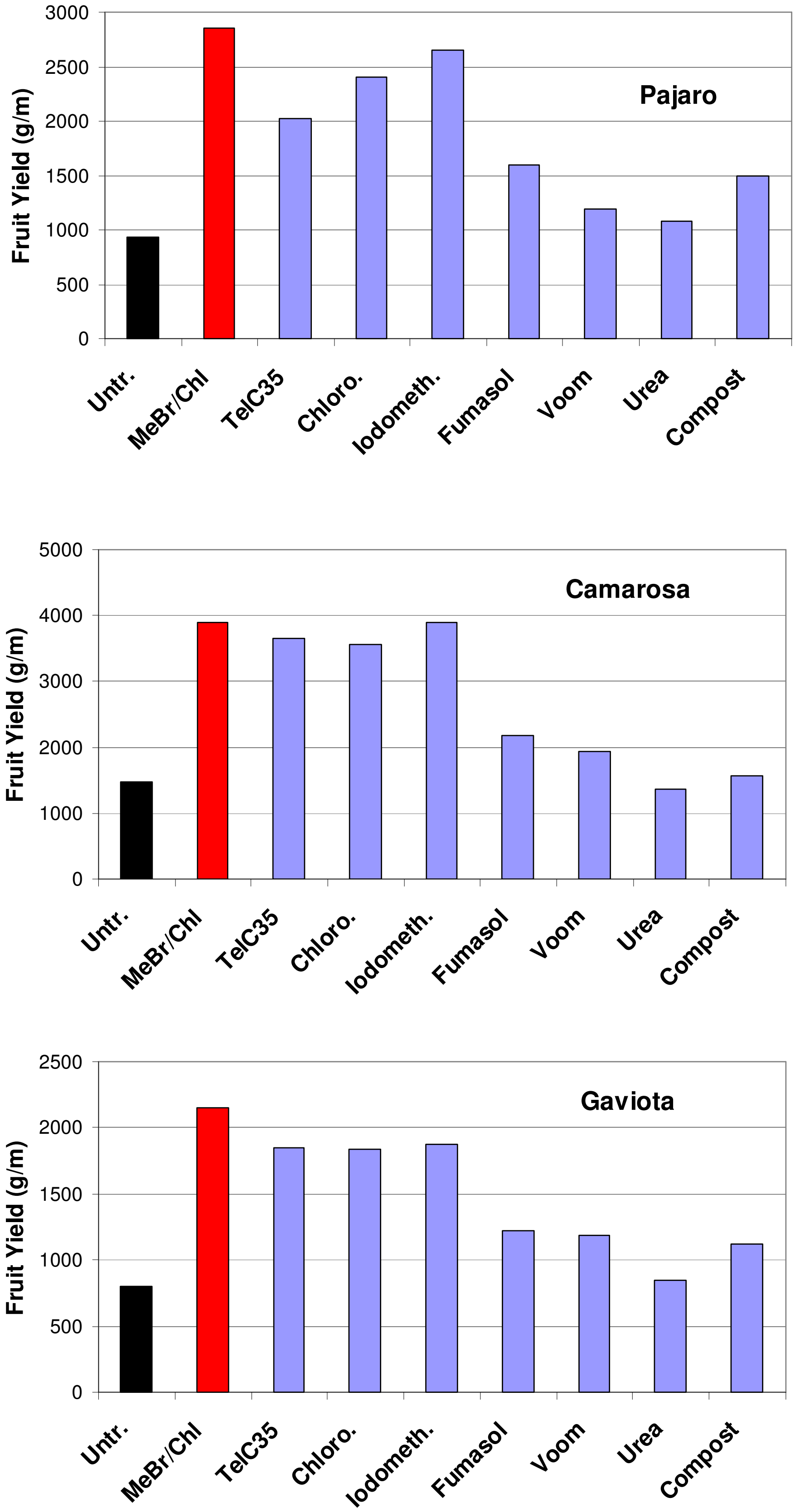
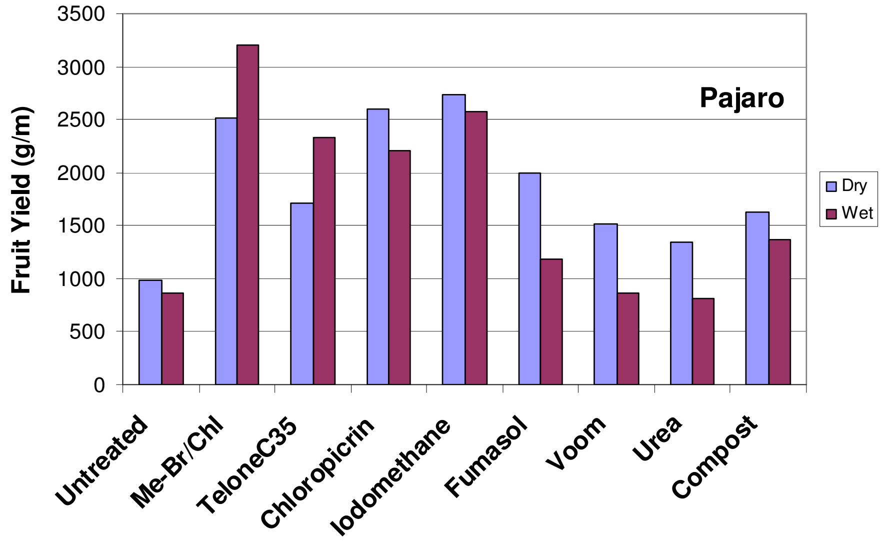
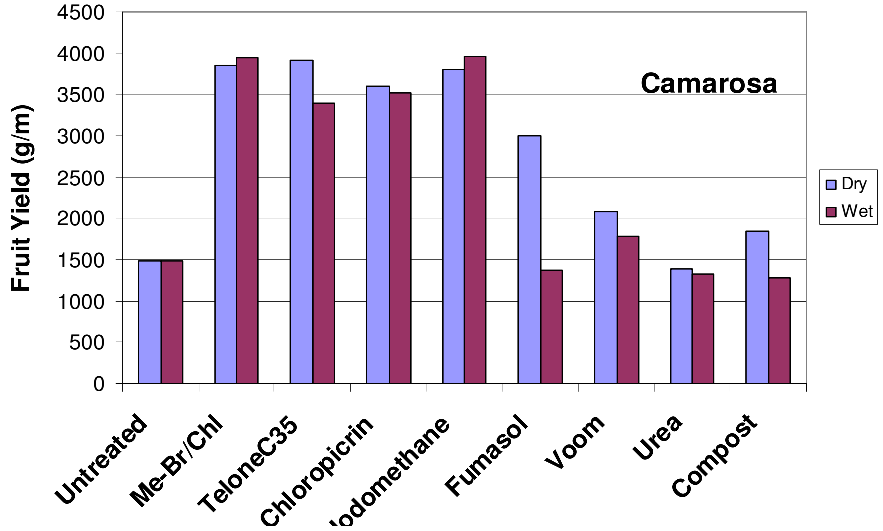


Figure 5.5. Total fruit yield, Main Roselea trial, 2005 season. Data are combined means of both dry and wet plots for each variety.





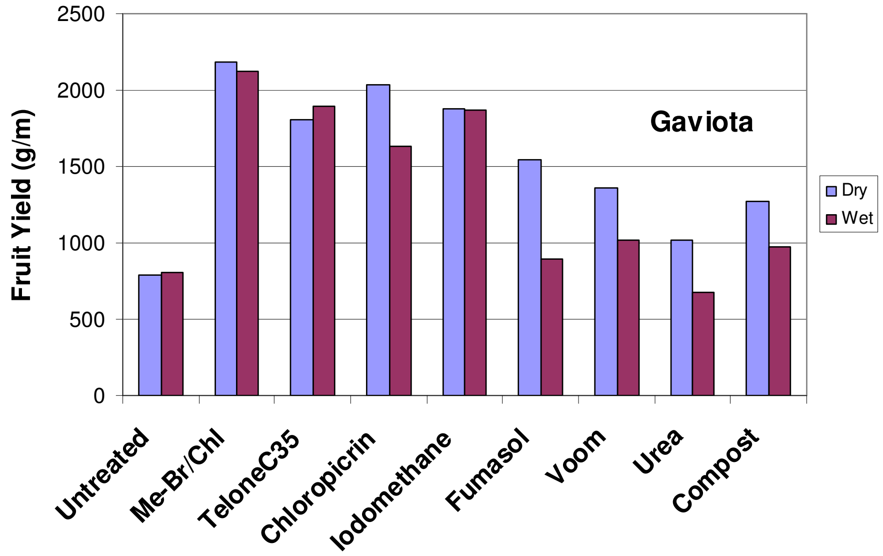


Figure 5.6. Total fruit yield, Main Roselea trial, 2005 season. Data are means of five replicate plots in ground that was either in good condition (dry) or poor condition (wet) during ground preparation and fumigation.

5.3 Roselea trial 2006

In May 2006, plots were re-established and the same treatments applied to the same plots as in 2005. The only change was that the mustard oil (Voom) treatment and biological product treatments were dropped from the trial. The chemical fumigants methyl bromide/chloropicrin 50:50, chloropicrin, Telone C35, Fumasol (metham sodium) and methyl iodide were re-applied to the same plots as in 2005. Urea plots were also re-treated, and compost and untreated beds were re-formed in the same ground, but without further treatment application. Five varieties ('Camarosa', 'Gaviota', 'Pajaro', 'Ventana' and 'Camino Real') were planted.

Final ground preparation and fumigation was very late (May 10), due to adverse weather conditions. Although soil temperatures were still adequate for fumigation (12-15 C) the soil was much wetter than ideal for fumigation. All plots were prepared in soil conditions even wetter than the 'wet' plots from the 2005 trial. Because of the high soil water content and decreasing soil temperatures, fumigant residues were slow to release, further delaying planting (to mid June). Half the plots were given excess water during winter and early spring to stimulate disease-conducive conditions. However, mid-winter was particularly wet, and it was difficult to get a differential between over-watered and normal plots without causing anaerobic conditions. Essentially, all plots remained wet throughout the winter.

A summary of fruit yield is presented in Figure 5.7. Fruit yield following treatment with any of the commercially available alternative fumigants was significantly lower than when fumigated with methyl bromide. A similar trend was seen with all varieties, suggesting the plant response was the result of less effective fumigation. On average, fruit yield in chloropicrin, Telone C35 and Fumasol-treated plots was 42, 38 and 36% less than that obtained in methyl bromide-treated plots. Yields with these fumigants were still greater than those with untreated controls and urea or compost treated plots, which ranged between 52 and 60% less than those with methyl bromide. The only fumigant that was close to methyl bromide in terms of fruit yield was methyl iodide. Although on average its yield was 14% less than methyl bromide, this difference was not statistically significant.

There was no obvious or consistent difference in response of plots kept excessively wet (by over-irrigation) throughout the winter and spring compared with those subject to ambient conditions. But, as noted above, conditions in all plots were much wetter than normal for most of the autumn and winter period.

Plant health results mirrored those seen for fruit yield. Methyl iodide was the only treatment close to methyl bromide in terms of overall plant health recorded at the end of the season (Figure 5.8). Telone C35, chloropicrin and Fumasol plots produced plants with inferior health to MB plots, although on average they were still superior to compost, urea and untreated controls.

The results from this trial demonstrate the importance of soil condition and managing root disease in the absence of methyl bromide. The wet soil conditions during soil preparation and fumigation, perhaps compounded by a subsequent wet winter, exposed weaknesses in most of the alternative fumigants in such conditions. A plausible interpretation is that alternative products with high boiling points and low vapour pressures such as Telone, chloropicrin and Fumasol did not move through the wet soil profile as thoroughly as did methyl bromide or methyl iodide with low boiling points and high vapour pressures. Additionally, the wet conditions during soil preparation also contributed to clod formation. These clods are likely to have acted as reservoirs for disease if they were not adequately penetrated by the fumigant gases. In the wet, disease-conducive conditions that followed, pathogens proliferated.

The 2006 trial is the first time in many years of trials at Roselea that plant performance with the alternative fumigants has not been close to that of methyl bromide. This is probably a result of the extremely wet soil conditions, and must be put in perspective with many other trials carried out on the same site. In good soil conditions, Telone C35 and chloropicrin have consistently performed well on this site, on average only slightly inferior to methyl bromide, despite high background levels of soil pathogens. The soil conditions in which the trial was established in 2006 were the sorts of conditions growers should be avoiding - too wet and too late in the season. These conditions cannot always be avoided, because of factors such as weather and contractor availability. However, the results from this trial indicate the problems that can occur with the alternative fumigants in such conditions, re-emphasising the importance of ensuring correct soil conditions for fumigation.

5.4 Impermeable barrier film trial 2006

In May 2006, a small trial investigating fumigant movement through soil was carried out at the Roselea site. The main aims were to determine: (1) whether there was better fumigant retention in beds covered with impermeable barrier films than with standard polythene, and (2) if the use of impermeable barrier films could allow reduced application rates of fumigants in the fruit industry.

Methyl bromide/chloropicrin 50:50 was shank injected into normal strawberry beds at half standard rate (250 kg/ha). Beds were covered with either standard low density polythene (40 µm) or a polyethylene/polyamide impermeable barrier film (50 µm Bromostop®). Gastec® tubes were used to take MB readings at 10 cm and 20 cm depth in the centre of the bed after 4 h, 24 h, 2 days, 7 days and 14 days. For comparison, measurements were also made in adjacent beds treated with full rate methyl bromide/chloropicrin (500 kg/ha), which were part of the main Roselea trial.

Results showed that the impermeable film retained methyl bromide in the soil for longer, and at higher concentration, than did standard 40 µm polythene (Figure 5.9), even when applied at half the rate. There were no apparent problems in laying the impermeable barrier film, and results suggest that it kept its integrity, despite the very wet soil conditions.

Results demonstrate the strong potential for impermeable barrier films to allow lower application rates of fumigants. This may provide a mechanism for increasing the cost-effectiveness of more expensive fumigants, such as methyl iodide. Unlike the strawberry runner industry, the use of impermeable barrier films in the fruit industry poses very little off-gassing issues because the film is not cut and remains in place for the entire season.

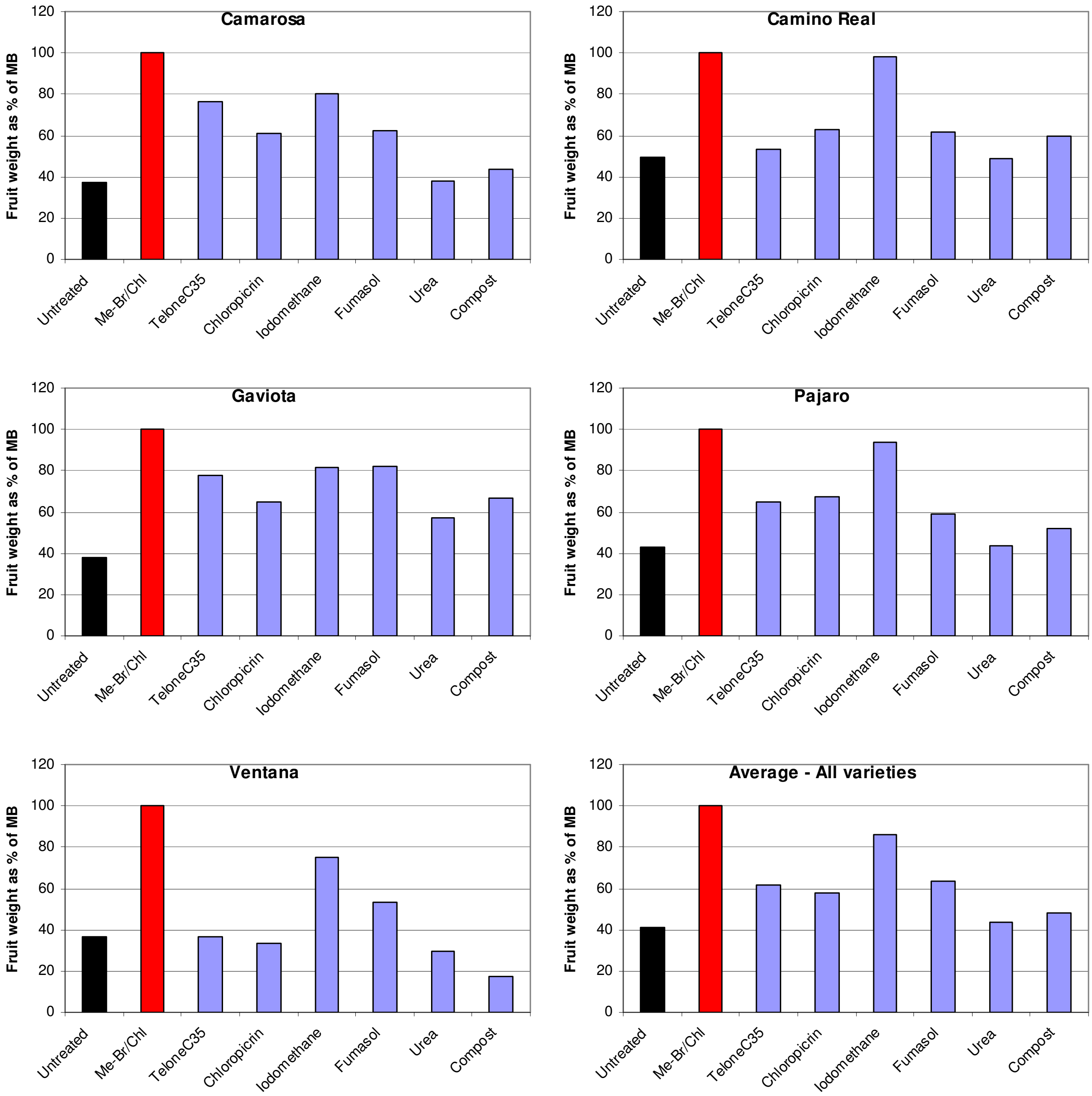


Figure 5.7. Average strawberry fruit yield following treatments with various fumigant and non-fumigant alternatives in wet conditions in the Roselea garden in 2006. Data expressed as a percentage of yield obtained with the standard methyl bromide/chloropicrin treatment.

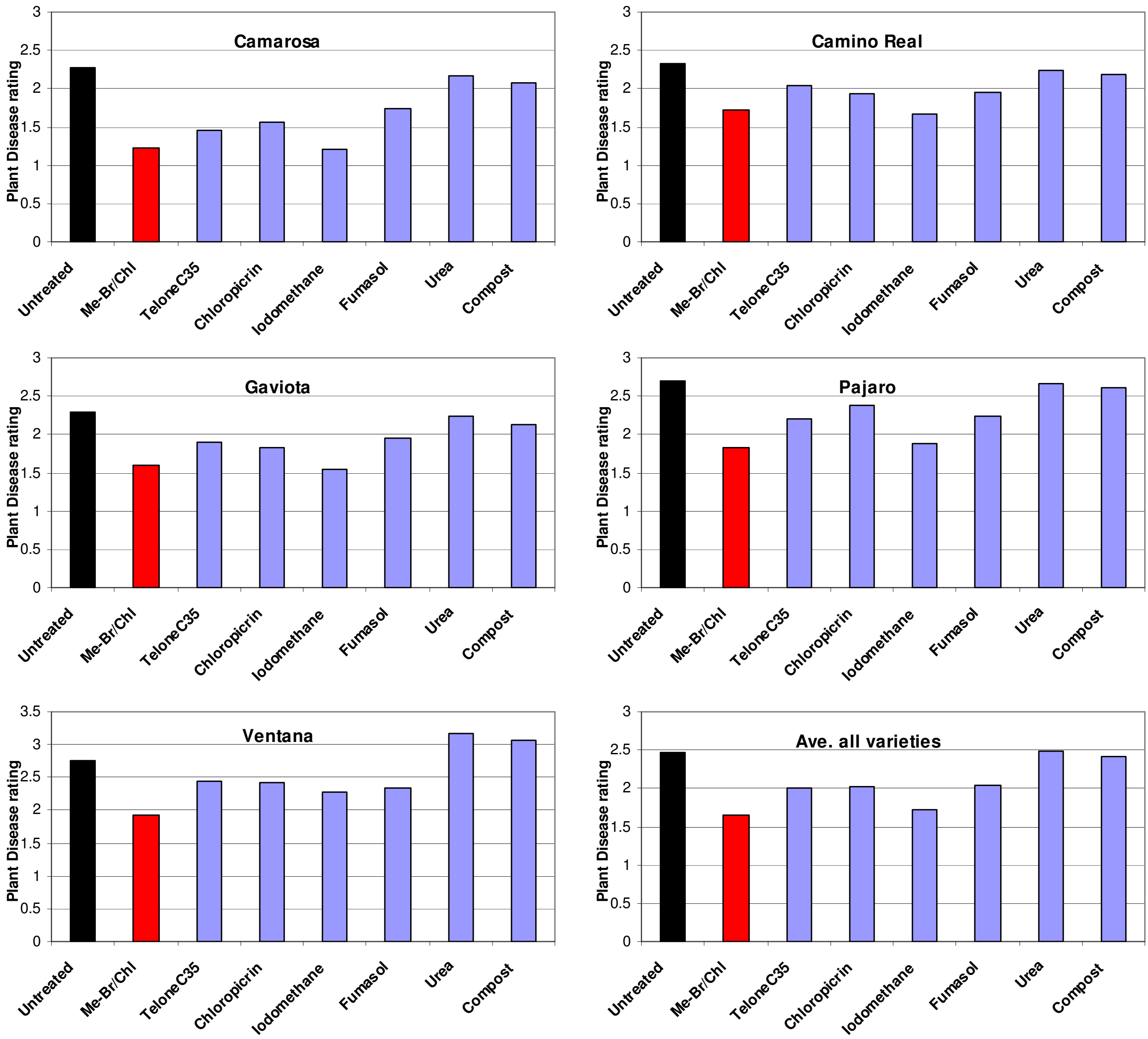


Figure 5.8. Average strawberry plant disease rating following treatment with various fumigant and non-fumigant alternatives in wet conditions in the Roselea garden in 2006. Plants were scored on a 0 to 4 scale where 0 was healthy and vigorous and 4 was dead.

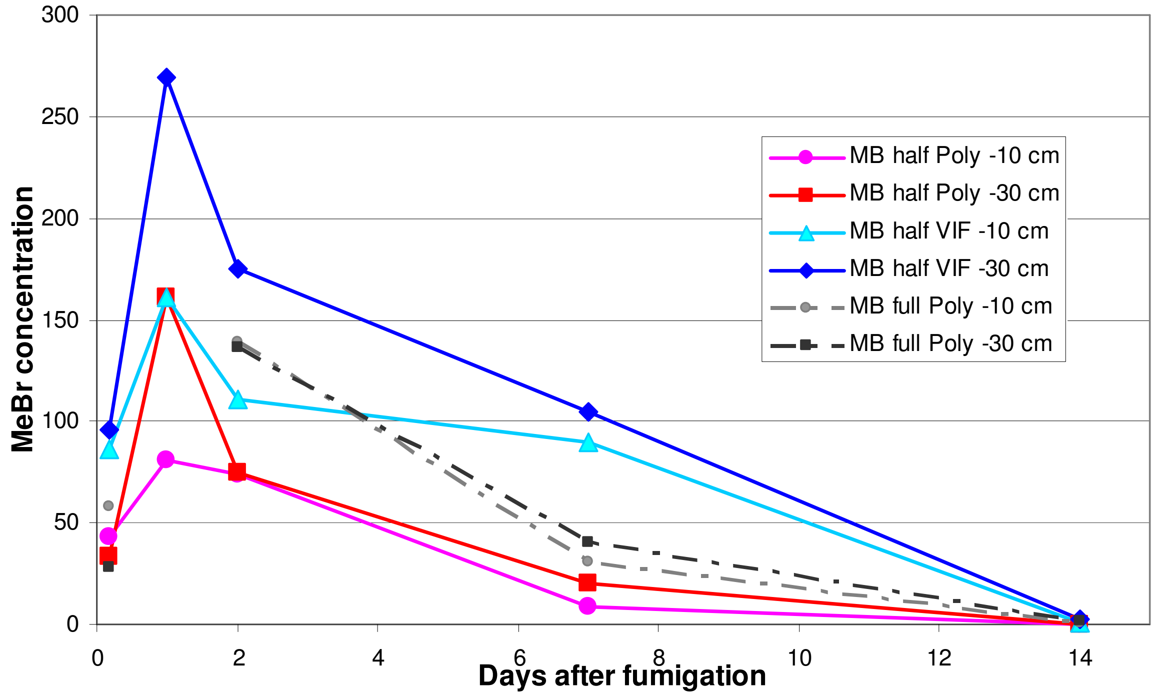


Figure 5.9. Methyl bromide (MB) gas concentrations in soil measured at various times after strawberry bed fumigation with half rate (250 kg/ha) or full rate (500 kg/ha) methyl bromide/chloropicrin 50:50, beneath impermeable barrier film (VIF) or standard polythene (Poly), Roselea 2006. Measurements taken at 10 and 30 cm depth, using Gastec® tubes.

5.5 Acknowledgements

This work was funded by Strawberry Growers New Zealand Inc., the MAF Sustainable Farming Fund, Elliott Technologies Ltd., and Horticulture Australia Ltd. The support of all these organisations is gratefully acknowledged. Brian Leicester has been invaluable in assisting with trials and discussing techniques and options.

Appendices

Appendix 5.1. The effects of fumigant/soil treatment on strawberry plant attributes measured in the main Roselea trial at the end of the 2005/06 season. Values are means of both “wet” and “dry” ends of the plot. Plant disease was scored on a 0 – 4 scale where 0 was healthy and 4 was dead. Root disease was scored on a 0 – 4 scale where 0, 1, 2, 3, 4 represented 0%, 25%, 50% 75% or 100% root decay.

‘Pajaro’

Fumigant	Average Height (mm)	Average Plant Disease Score	Average Root Disease Score	Total Fruit Weight (g/m)	Average Plant Dry Weight (g)
Chloropicrin	227.9	0.510	2.312	2400	124.9
Compost	182.8	1.525	2.987	1497	97.7
Fumasol	152.4	1.445	2.837	1590	70.8
Iodomethane	206.2	0.640	2.175	2654	135.5
Me-Br/Chl	250.6	0.425	1.950	2856	139.3
TeloneC35	203.9	1.020	2.325	2021	86.6
Untreated	103.8	2.160	3.075	929	31.9
Urea	125.9	1.765	2.875	1081	64.7
Voom	128.1	1.802	3.162	1193	34.4
Tukey’s LSD (5%)	82.14	1.2173	1.0090	1128.7	116.47

‘Camarosa’

Fumigant	Average Height (mm)	Average Plant Disease Score	Average Root Disease Score	Total Fruit Weight (g/m)	Average Plant Dry Weight (g)
Chloropicrin	231.9	0.850	1.900	3558	159.8
Compost	169.5	1.317	2.887	1564	70.2
Fumasol	185.5	1.400	2.800	2181	93.6
Iodomethane	209.9	0.975	2.112	3885	135.3
Me-Br/Chl	232.3	0.717	1.662	3902	190.5
TeloneC35	215.9	1.017	2.050	3655	128.9
Untreated	124.6	1.992	3.212	1484	14.9
Urea	125.7	1.958	3.125	1357	33.4
Voom	138.8	1.683	2.975	1936	37.0
Tukey’s LSD (5%)	71.24	1.0761	0.7074	1680.5	158.13

'Gaviota'

Fumigant	Average Height (mm)	Average Plant Disease Score	Average Root Disease Score	Total Fruit Weight (g/m)	Average Plant Dry Weight (g)
Chloropicrin	231.5	0.3125	1.850	1834	83.1
Compost	203.6	0.8259	2.475	1123	48.9
Fumasol	170.1	1.1062	2.425	1222	36.0
Iodomethane	227.6	0.3909	1.750	1876	61.4
Me-Br/Chl	240.6	0.3187	1.587	2154	69.9
TeloneC35	231.7	0.4009	1.787	1850	73.2
Untreated	125.3	1.6562	2.875	801	9.4
Urea	138.3	1.4750	2.600	845	26.9
Voom	169.8	1.1125	2.612	1188	28.1
Tukey's LSD (5%)	72.13	1.0253	0.7657	976.4	79.04

Appendix 5.2. The effects of fumigant and soil condition during soil preparation and fumigation on strawberry plant attributes measured in the main Roselea trial, 2005/06. Plant disease was scored on a 0 – 4 scale where 0 was healthy and 4 was dead. Root disease was scored on a 0 – 4 scale where 0, 1, 2, 3, 4 represented 0%, 25%, 50% 75% or 100% root decay. Values are means of five replicate plots.

'Pajaro'

Fumigant	Average Height		Average Health Score		Average Root Disease Score		Total Fruit Weight		Average Plant Weight	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Chloropicrin	239.2	216.5	0.51	0.51	2.325	2.300	2600	2200	117.2	132.6
Compost	214.3	151.3	1.54	1.51	2.800	3.175	1624	1370	103.8	91.6
Fumasol	171.9	132.9	1.30	1.59	2.750	2.925	2001	1179	91.4	50.2
Iodomethane	212.6	199.8	0.52	0.76	1.925	2.425	2735	2573	153.0	118.0
Me-Br/Chl	223.6	277.5	0.61	0.24	1.700	2.200	2511	3202	129.2	149.4
TeloneC35	201.5	206.2	1.06	0.98	2.100	2.550	1715	2328	59.2	114
Untreated	108.1	99.4	1.99	2.33	3.050	3.100	992	866	40.4	23.4
Urea	144.3	107.4	1.67	1.86	2.725	3.025	1345	817	82.2	47.2
Voom	144.0	112.1	1.65	1.96	3.150	3.175	1522	864	38.0	30.8
Tukey's LSD (5%)	115.87		1.718		1.6457		1642.5		166.04	

'Camarosa'

Fumigant	Average Height		Average Health Score		Average Root Disease Score		Total Fruit Weight		Average Plant Weight	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Chloropicrin	240.3	223.5	0.733	0.967	1.675	2.125	3599	3518	166.4	153.2
Compost	175.1	163.8	1.267	1.367	2.750	3.025	1853	1276	82.6	57.8
Fumasol	217.8	153.3	1.233	1.567	2.475	3.125	2993	1369	154.6	32.6
Iodomethane	205.2	214.7	0.967	0.983	2.175	2.050	3812	3957	137.4	133.2
Me-Br/Chl	234.8	229.8	0.667	0.767	1.300	2.025	3852	3952	215.4	165.6
TeloneC35	237.0	194.8	0.667	1.367	1.500	2.600	3918	3392	132.4	125.4
Untreated	116.0	133.2	2.050	1.933	3.225	3.200	1477	1492	22.0	7.8
Urea	129.7	121.7	1.967	1.950	3.175	3.075	1391	1323	46.2	20.6
Voom	145.5	132.2	1.733	1.633	2.925	3.025	2088	1784	37.6	36.4
Tukey's LSD (5%)	130.25		1.912		1.3601		2690.3		236.53	

'Gaviota'

Fumigant	Average Height		Average Health Score		Average Root Disease Score		Total Fruit Weight		Average Plant Weight	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Chloropicrin	244.6	218.4	0.187	0.438	1.675	2.025	2035	1632	83.8	82.4
Compost	217.0	190.2	0.614	1.038	2.250	2.700	1271	975	70.0	27.8
Fumasol	202.4	137.9	0.837	1.375	2.000	2.850	1545	898	52.2	19.8
Iodomethane	228.8	226.5	0.339	0.443	1.500	2.000	1881	1872	77.4	45.4
Me-Br/Chl	224.9	256.4	0.325	0.312	1.300	1.875	2186	2123	85.0	54.8
Telone C35	225.2	238.1	0.412	0.389	1.500	2.075	1803	1897	79.8	66.6
Untreated	119.1	131.4	1.675	1.637	2.875	2.875	792	811	6.4	12.4
Urea	151.0	125.6	1.275	1.675	2.300	2.900	1015	675	25.6	28.2
Voom	186.3	153.4	0.975	1.250	2.600	2.625	1359	1018	30.8	25.4
Tukey's LSD (5%)	109.65		1.3982		1.182		1284.3		117.66	

6 Methyl bromide emission control strategies

6.1 Summary

This preliminary trial showed that impermeable (Orgalloy) and semi-impermeable (Canslit) barrier films are about 10 times more effective in preventing MB flux to the atmosphere than standard low-density polyethylene (LDPE), while the film is in place. Following the removal of films from soil (6 days), however, as much as 60% of applied MB escaped when the impermeable and semi-impermeable films were cut. Therefore, impermeable and semi-impermeable films need to be retained on the soil for significantly longer periods than 6 days to be effective emission control strategies for MB and other fumigants. For plasticulture industries such as strawberry fruit and vegetables, where films remain in place for the entire season, impermeable and semi-impermeable films offer a more environmentally responsible production method than standard films, and may also allow reduced application rates of fumigants. For broad-acre horticultural industries such as strawberry runners and outdoor flowers, however, the timing of film removal (as soon as 2-4 days after application) is totally dependant on threat of rain and the substantial erosion problems this causes from water running off plastic. Therefore the use of impermeable and semi-impermeable films for these industries represents a potential off-gassing and OH&S hazard to operators, and may only be safe if used with future fumigant scrubbing or re-capture technologies.

In the current trial, application rates of MB at 25 g/m^2 (MB:Pic 50:50, 50 g/m^2) and 12.5 g/m^2 (MB:Pic 50:50, 25 g/m^2) were similarly effective in stimulating strawberry runner growth and controlling pathogens and weeds (note: application rates of MB below 25 g/m^2 are not currently registered in Australia). The use of impermeable or semi-impermeable films did not improve the efficacy of MB, even at very low rates (6.25 g/m^2, MB:Pic 50:50 12.5 g/m^2). Again, this is probably due to the short period of time that films were in place. The implications of these findings are that in heavy soils under cool climates it appears possible to achieve significant emission controls using reduced application rates of MB in combination with LDPE. This can only happen if further scale-up work is approved and funded to confirm the initial findings.

6.2 Aim

To evaluate emission reduction strategies for methyl bromide for soil disinfestation and strawberry runner production in Australia.

6.3 Method

Fumigated: June 2005

Application: Broad-acre injection to a soil depth of 20 cm through tynes spaced 20 cm apart.
Barrier film removed after 6 days.
Soil type: clay loam, pH 5.8
Soil temperature range (at 10cm depth) over the fumigation period: 3.8 – 18.2°C

Treatments: *Fumigants (Main plots):*
MB:Pic (50:50) (500 kg/ha* ≡ 25 g/m² of MB)
MB:Pic (50:50) (250 kg/ha* ≡ 12.5 g/m² of MB)
MB:Pic (50:50) (125 kg/ha* ≡ 6.25 g/m² of MB)
Untreated (0 g/m² of MB)

*note: fumigant cylinders were weighed post application to ensure application rates were as accurate as possible

Barrier Films (Split plots):
LDPE (low-density polyethylene)
Orgalloy (low permeability film, equivalent to VIF)
Canslit (semi-permeable film, not equivalent to VIF)

Design: Randomised split-plot design with 4 blocks. Individual plots were 20 m long and 2.7m wide.

Planting: October 2005 (4 months after fumigation)
Single row per plot (0.5 m spacing)
Strawberry variety 'Gaviota'

Assessments:
Fumigant residues: At 4 48, and 144 hours after fumigation, concentrations of MB and Pic in the gas phase were measured in soil atmosphere at depths of 10 and 30 cm. Residues were collected in tubes containing activated carbon, extracted in the laboratory, and detected and quantified using GC/MS.
Fumigant Emissions: Air samples above selected treatments were collected over a set period of time (15 min) using a stainless steel flux chamber (Cox et al., 2004). Samples were analysed for MB using GC-MSD-ADS and FTIR (Prin et al., 2000; Fraser et al., 2005), and flux rates through films calculated.
Pathogen Survival: At fumigation, muslin bags containing inoculum of *Rhizoctonia fragariae* (hyphae on millet seed), *Verticillium dahliae* (microsclerotia), and *Sclerotium rolfsii* (sclerotia) were buried at depths of 10 and 30 cm between the tyne line in each plot. Bags were recovered after 5 days, and pathogen viability determined by plating 10 pieces of inoculum of each pathogen onto PDA.
Weed emergence: At 4 months after fumigation (September 2005), weed emergence was assessed by counting the total number of weeds contained in 2 randomly thrown quadrats (0.16m²) per plot.

Final runner yield: At harvest (July, 2006; 9 months after planting) the numbers of strawberry runners contained in 2 randomly selected 0.5 m lengths of row per plot were counted.

6.4 Results

Fumigant residues: Concentrations of gaseous MB and Pic in soil increased with increasing application rate (Fig 6.1). There was no difference in the concentration of gaseous MB or Pic in soil under different barrier films (Fig 6.2). At the 4 and 48-hour measurements, concentrations of MB and Pic were higher at soil depths of 10 cm than at 30 cm (Fig 6.3). There were no interactions between barrier film, application rates or soil depth for MB or Pic concentrations in soil.

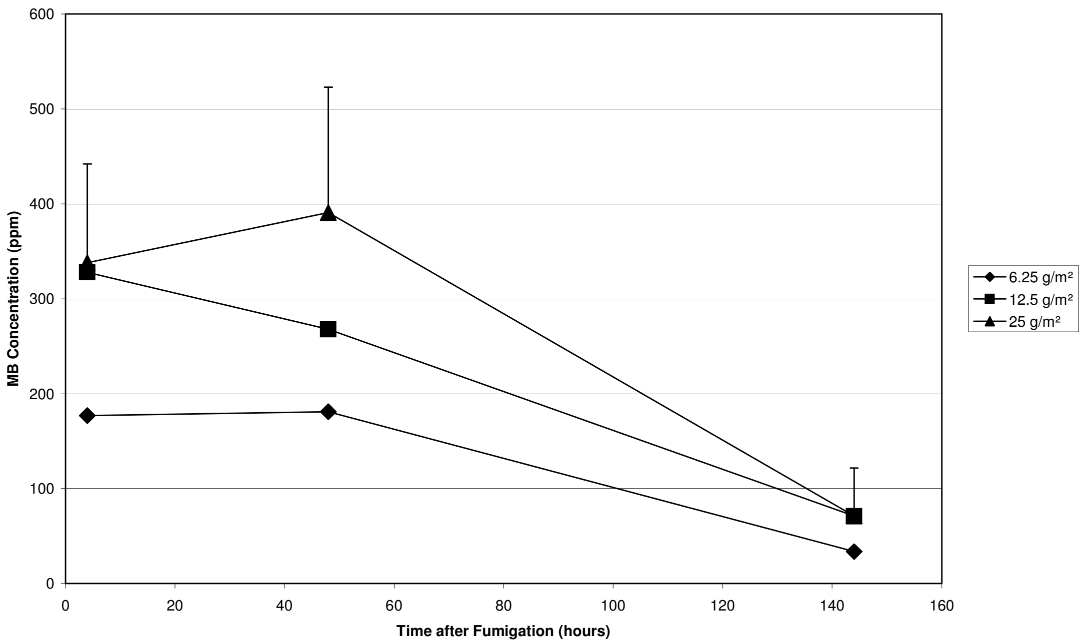


Figure 6.1. Average concentrations of gaseous MB in soil over time following application of MB at rates of 6.25, 12.5, and 25 g/m^2 (applied as MB:Pic 50:50 at rates of 12.5, 25, and 50 g/m^2 , respectively). Bars represent LSDs where *p* = 0.05.

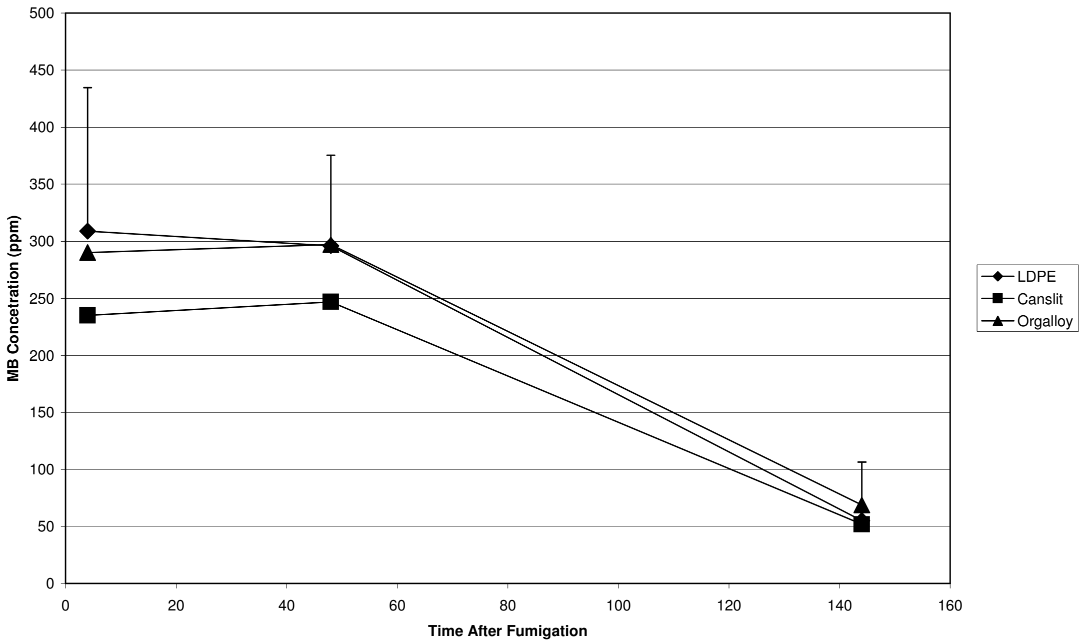


Figure 6.2. Average concentrations of gaseous MB in soil over time following application of MB:Pic 50:50 under different barrier films. Bars represent LSDs where $p = 0.05$.

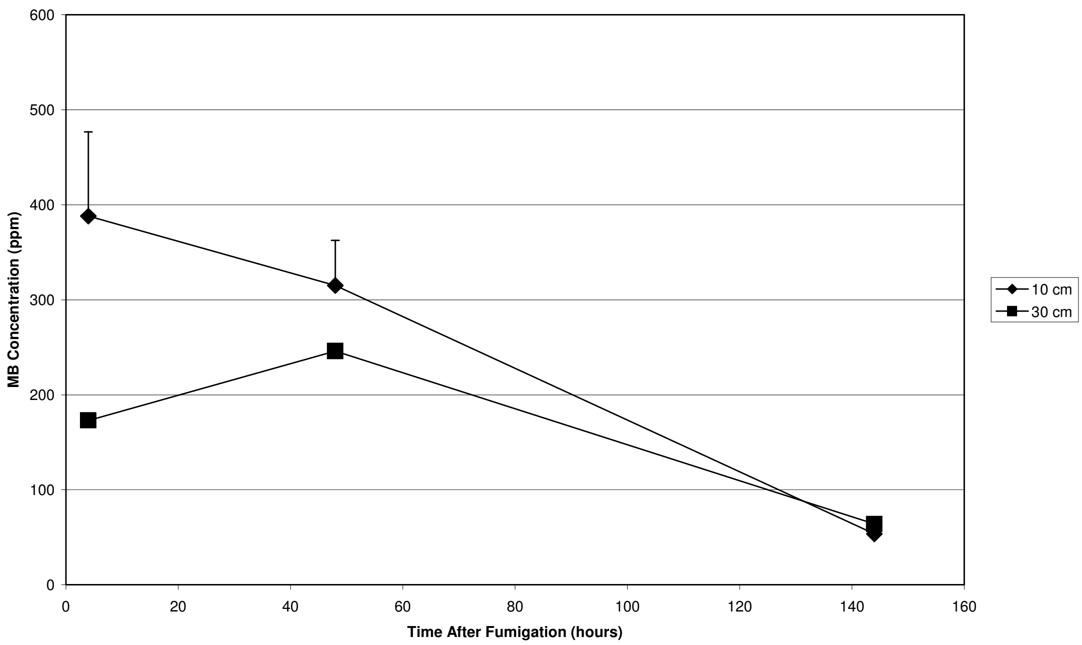


Figure 6.3. Average concentrations of gaseous MB at different soil depths following application of MB:Pic 50:50. Bars represent LSDs where $p = 0.05$.

Fumigant Emissions: On average, impermeable films reduced fluxes of MB by between 85 – 90% compared with standard LDPE films, when the films were in place. In plots treated with MB at 25 g/m², average emission rates of MB through films were 0.12 g/m²/hr for LDPE; 0.02 g/m²/hr for Orgalloy; and 0.015 g/m²/hr for Canslit (Fig 6.4). Overall, emission rates were lower in plots treated with lower rates of MB (ie 12.5 g/m²): 0.01 g/m²/hr for LDPE; 0.002 g/m²/hr for Canslit, and 0.001 g/m²/hr for Orgalloy (Fig 6.5).

When films were lifted (6 days after application), the average flux of MB through soils covered by LDPE was 0.03 g/m²/hr, irrespective of MB application rate. In contrast, fluxes from soils covered by impermeable films (Canslit and Orgalloy) were 0.47 g/m²/hr and 0.11 g/m²/hr for applications rates of 25 and 12.5 g/m² of MB, respectively.

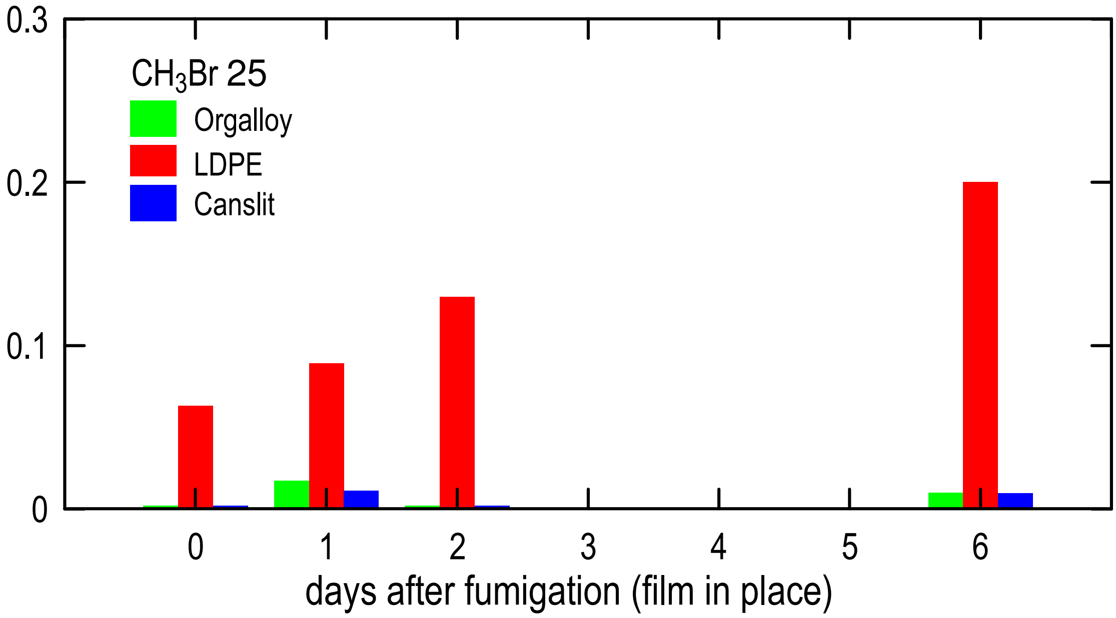


Figure 6.4. MB fluxes (g/m²/hr) from soil through three barrier film types at Toolangi, Victoria (MB application rate of 25 g/m²).

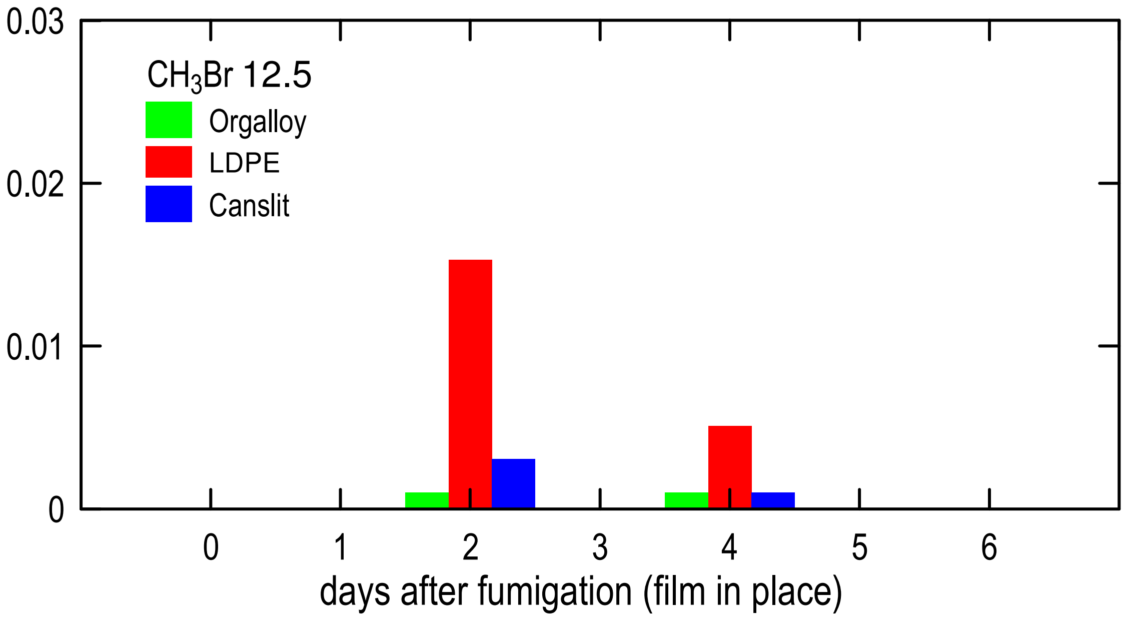


Figure 6.5. MB fluxes (g/m²/hr) from soil through three barrier film types at Toolangi, Victoria (MB application rate of 12.5 g/m²).

Pathogen Survival: All rates of MB reduced the viability of all pathogens from 100% in untreated plots to 0%, irrespective of barrier film type.

Weed Emergence: There was no difference in weed emergence between plots sealed with different barrier films. Weed emergence declined as the application rate of MB increased (Fig 6.6). MB applied at 25 g/m² and 12.5 g/m² gave equivalent weed control. Weed emergence in plots treated with MB at 6.25 g/m² had higher weed emergence than plots treated with MB at 25 g/m² or 12.5 g/m². There was no interaction between barrier film and application rate for weed emergence.

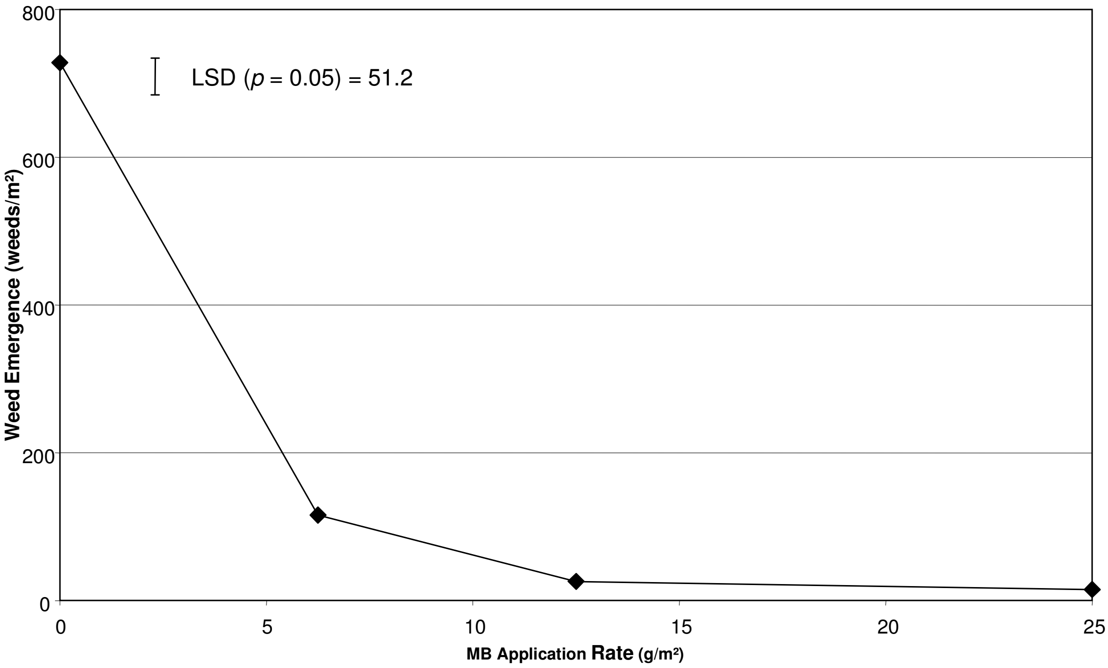


Figure 6.6. Weed emergence 4-months after treatment following application of MB as MB:Pic 50:50 at various application rates (eg MB application rate of 25 g/m² ≡ 50 g/m² of MB:Pic 50:50).

Yield: There was no difference in runner yields between plots sealed with different barrier films (Fig 6.7). Runner yields tended to increase with increasing application rate of MB (Fig 6.8). However, runner yields in plots treated with MB at 12.5 g/m² were equivalent to those treated at 25 g/m². There was no interaction between barrier film and application rate for yield.

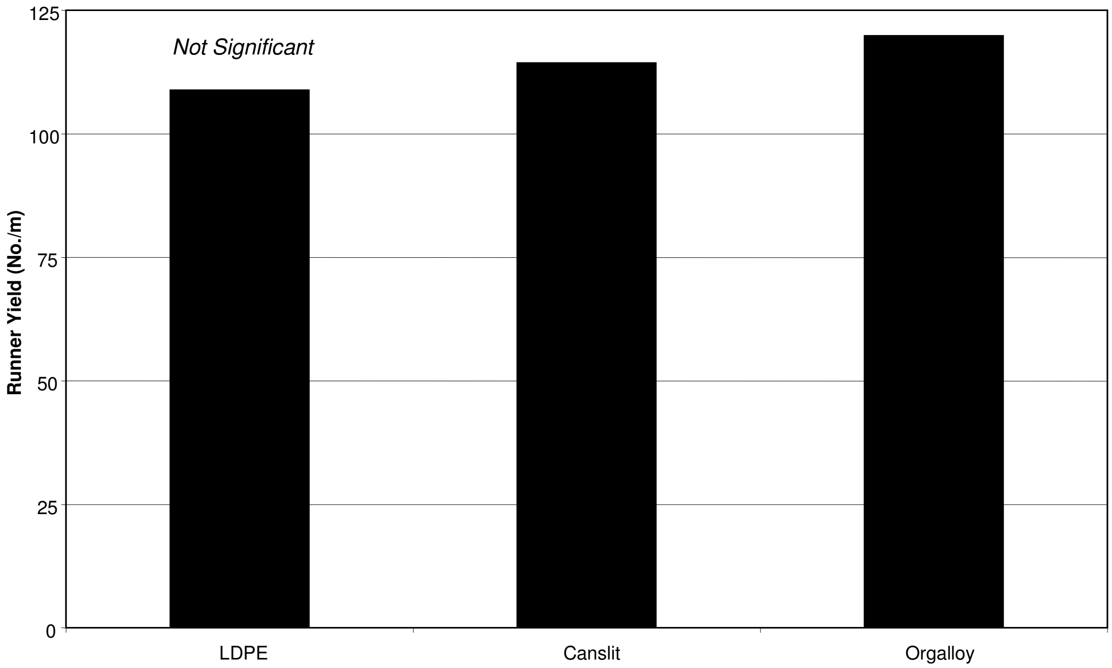


Figure 6.7. Average runner yields in plots treated with MB:Pic 50:50 and sealed with various barrier films.

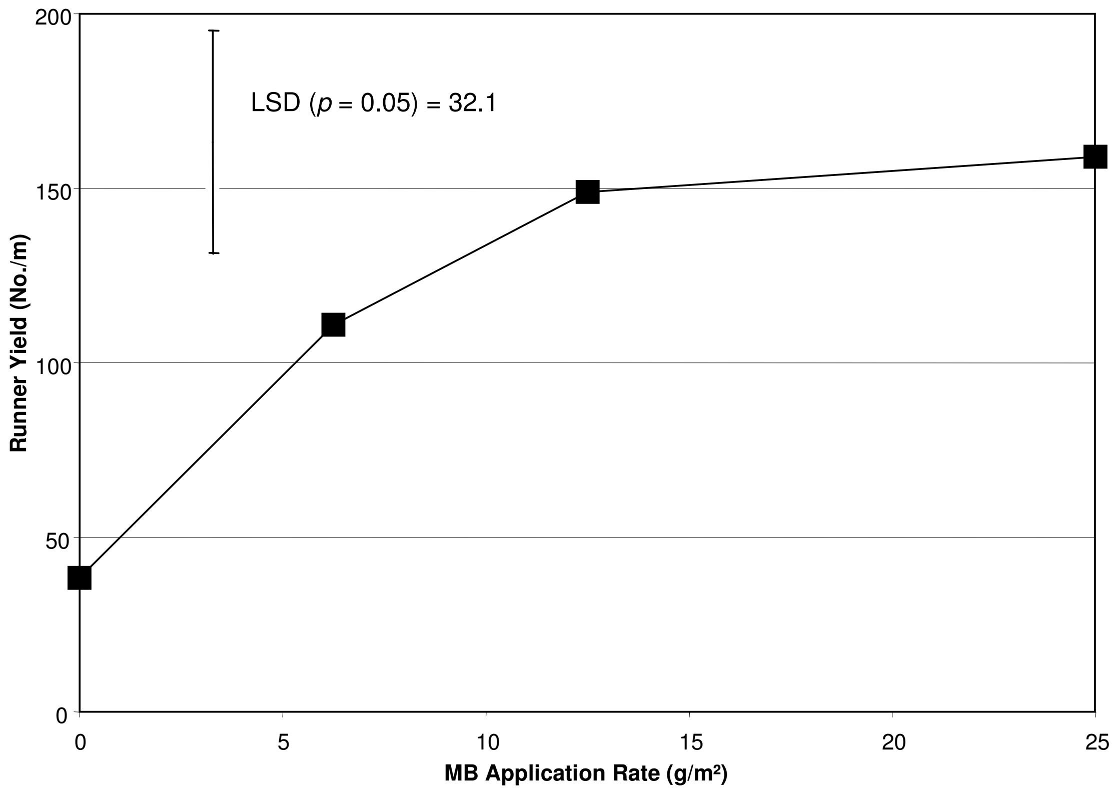


Figure 6.8. Average runner yields in plots treated with MB as MB:Pic 50:50 at various application rates (eg MB application rate of 25 g/m² ≡ 50 g/m² of MB:Pic 50:50).

6.5 Discussion

Low permeability films were 5-10 times more effective at blocking MB emissions to the atmosphere than standard LDPE, but only when the films were in place. Following the removal of films from soil (6 days), however, there was a measured flush in MB emissions from plots covered with impermeable and semi-impermeable films. Assuming that degradation rates of MB in soils covered with impermeable, semi-impermeable, and LDPE films are similar (ie 25% of applied MB); then as much as 60% of applied MB escaped when the impermeable and semi-impermeable films were removed in this trial (after 6 days) - most of this during the first day of film removal. Therefore, impermeable and semi-impermeable films need to be retained on the soil for significantly longer periods than 6 days to be effective emission control strategies for MB and other fumigants. For plasticulture industries such as strawberry fruit and vegetables, where films remain in place for the entire season, impermeable and semi-impermeable films offer a more environmentally responsible production method than standard films, and may also allow reduced application rates of fumigants. For broad-acre horticultural industries such as strawberry runners and outdoor flowers, however, the timing of film removal (as soon as 2-4 days after application) is totally dependant on threat of rain and the substantial erosion problems this causes from water running off plastic. Therefore the use of impermeable and semi-impermeable films for these industries represents a potential off-gassing and OH&S hazard to operators, and may only be safe if used with future fumigant scrubbing or re-capture technologies.

This preliminary trial suggests that the most effective emission control strategy for MB in the strawberry runner industry (under cool season conditions in heavy soils) is to reduce application rates under standard LDPE (note that application rates of MB:Pic 50:50 below 50 g/m^2 are not registered in Australia). Reducing MB application rates from 25 g/m^2 to 12.5 g/m^2 had no detrimental impact on pathogen control, weed control, or final yields. However, reducing rates to 6.25 g/m^2 was not effective for weed control and runner yields. The ability of lower MB application rates (12.5 g/m^2) to deliver pest control equivalent to standard rates (25 g/m^2) was not dependent on the use of low-permeability barrier films.

Continued research is required to determine:

1. The total MB balances in the system (ie MB in the liquid in addition to the gas phase).
2. Critical thresholds for effective doses of MB for different mixtures of MB:Pic (eg 30:70)
3. A greater number of sample points to provide greater surety of efficacy for the nursery industry and to demonstrate their certification standards are maintained
4. Scale-up issues with the use of lower doses of MB under commercial conditions in the runner industry to support registration and adoption.

7 Technology transfer to support phase-out of methyl bromide in Australian horticulture

7.1 Outcomes

The communication program implemented through this project has had the following impacts:

- *Increased awareness amongst growers of new MB alternatives.* This is measured by the willingness of growers to commence commercial trialling of new alternatives (eg 70% of strawberry runner growers have commenced commercial trials with methyl iodide). These commercial trials are currently offsetting Australia's use of MB.
- *Reduced number of industries applying for critical-use exemptions to retain the use of MB* (reduced by 80% since the commencement of this project). This is partly due to the anticipated availability of the MB alternatives identified and communicated through this project.
- *Reduced MB use in Australian horticulture* (reduced by more than 100 tonnes pa since the commencement of this project).
- *Strong, ongoing linkages formed between Australian and international researchers on soil disinfestation.* This will ensure that Australian growers have continued access to world's-best practice in soil disinfestation and MB alternatives.

7.2 Technology transfer program

Communication Plan

The following communication plan was established at the commencement of this project:

Target Audience:

- Horticultural growers affected by the MB phase-out, particularly those holding critical-use exemptions (Queensland strawberry fruit, Victorian strawberry fruit, Victorian and Queensland strawberry runners, Victorian indoor flowers, Queensland indoor flowers) or under threat of applying for them (Tobacco and Turf industries);
- Fumigant contractors and chemical companies (eg Dow AgroSciences, Arysta LifeSciences);
- Policy and regulatory authorities (eg Victorian Strawberry Industry Certification Authority, APVMA);
- National and international scientific colleagues.

Communication Message: New alternatives are available and in development that will assist growers in phasing out MB.

Desired Response: Increased awareness of new MB alternatives, and a willingness by growers to conduct commercial trials of these alternatives.

Delivery of the Communication Plan

This project developed and conducted a technology transfer program in close collaboration with the National MB Alternatives Communication Program (HG01005), and other MB alternatives research projects (eg HG04018, TB04001, HG01045). Working through the National Program allowed this project to communicate project outcomes to more than 2000 horticultural growers affected by the MB phase-out nationally. For example, this project assisted in developing and distributing to growers a CD-Rom of all MB alternatives research and communication articles published over the last 10 years. Outcomes from this project were also posted on the National Program's website (www.dpi.vic.gov.au/farming), in addition to industry-based websites (eg strawberries: www.vicstrawberries.com.au).

On average, this project delivered more than one publication every month and one communication activity every two months for the life of the project. Publications ranged from scientific journal articles to industry newsletters. Communication activities were conducted across the country and ranged from oral presentations at field days and grower meetings to personal visits with leading growers in the industry. One particularly successful communication event was a field day 'Getting the most from MB alternatives' for the strawberry fruit industry. The event was held at one of the farms conducting commercial trials of new MB alternatives (MI:Pic and Telone C35), and attracted 65 growers (*c.* 30 % of the Victorian strawberry fruit industry). The day was successful because it was co-ordinated and run through the industry development officer and industry association (Victorian Strawberry Industry Development Committee). The day allowed the host grower to showcase the commercial trial and give a first-hand account of his experiences with the application and performance of the alternatives. It also included a facilitated discussion between growers, fumigant suppliers and scientists on the ongoing issues with alternative fumigants. Many of the issues identified (eg long, inconsistent plant-back times with alternative fumigants) will be resolved through the development and registration of the products identified in this project, particularly methyl iodide.

Evaluation of the Communication Plan

At the commencement of this project, five Australian horticultural industries (Queensland strawberry fruit, Victorian strawberry fruit, Victorian and Queensland strawberry runners, Queensland indoor flowers and Victorian indoor flowers) had applied for, and were granted, critical-use exemptions (CUE) to retain the use of MB for soil disinfestation purposes. At the completion of this project, only one industry (Victorian strawberry runners) is still applying for a CUE. This reduction in MB use (over 100 tonnes pa) is due in part to this project increasing the confidence of growers in using currently registered alternative and in demonstrating that new alternatives (such and methyl iodide) are likely to become available in the near future.

The communication program implemented in this program achieved its desired outcome. It increased grower awareness of new alternatives to MB and application technologies by communicating with more than 2000 growers affected by the MB phase-out nationally. This increased awareness is measured by the willingness of growers to undertake commercial scale trialling of the alternatives identified in this project. For example, following the APVMA's approval of an experimental-use permit (EUP), 70% of strawberry runner growers have set up commercial trials of methyl iodide. These trials are currently offsetting Australia's use of MB, and will assist in driving adoption of alternatives in this industry.

Similarly, 79% of the Victorian strawberry fruit industry (VSIDC members) voted in favour of conducting commercial trials with methyl iodide, once an EUP is granted in that industry.

Industry and Project Team Awards

Both Australian industry and the project team were recognised internationally for their efforts in the phase-out methyl bromide and for ozone protection. These awards demonstrate the strong international reputation Australian horticultural industries have achieved for environmental stewardship during the MB phase-out process.

2006 – Australian Strawberry and Vegetable Industry, International Ozone Protection Award, United States of America's Environmental Protection Agency

2007 – Dr Ian Porter, Best of the Best Award, Special Ozone Protection Award to mark the 20th Anniversary of the Montreal Protocol, United States of America's Environmental Protection Agency

2007 – Australian Strawberry and Vegetable Industry, Best of the Best Award, Special Ozone Protection Award to mark the 20th Anniversary of the Montreal Protocol, United States of America's Environmental Protection Agency

2007 – DPI Vic's MB Alternatives Team, The Montreal Protocol Innovators Award, United Nations Environment Programme.

7.3 Publications

Scientific Journal Papers and Book Chapters:

Mattner, S.W., Gounder R.K., Mann, R.C., Porter, I.J., Matthiessen, J.N., Ren, Y.L., and M. Sarwar (2006). Ethanedinitrile – A novel soil fumigant for strawberry production. *Acta Horticulturae* **708**: 197-204.

Porter, I.J., Brett, R.W., Mattner, S.W., and H.E. Donohoe. 2006. Implications of the increased growth response after fumigation on future crop protection and crop production strategies. *Acta Horticulturae* **698**: 229-237.

Porter, I.J., Mattner, S.W., Banks, J., and P. Fraser (2006). Impact of global methyl bromide phase-out on the sustainability of strawberry industries. *Acta Horticulturae* **708**: 179-186.

Porter, I.J., Mattner, S.W., Mann, R.C., and R.K. Gounder (2006). Strawberry nurseries: Summaries of alternatives and trials in different geographic regions. *Acta Horticulturae* **708**: 187-192.

Mattner, S.W., Porter, I.J., Gounder, R.K., Shanks, A.L., and Allen, D. (2008) Factors that impact on the ability of biofumigants to suppress fungal pathogens and weeds of strawberry. Crop Protection. (in press).

Shanks, A.L., Mattner, S.W., Porter, I.J., and Tostovrsnik N.S. (2007). Reflections from the Australian experience in phasing out methyl bromide for minimising the impact of future compliance with the Montreal Protocol. Australasian Journal of Environmental Management (in submission).

Mattner, S.W., and Porter, I.J. (2006). Case Study 10. Australia - Phase-out of methyl bromide in the strawberry fruit industry. *In* .MBTOC (eds). United Nations Environment Programme 2006 Report of the Methyl Bromide Technical Options Committee pp 374-378. UNEP, Nairobi, Kenya. ISBN 978-92-807-2827-9.

CD-Rom:

Trinder, L.E., Tostovrsnik, N.S., Shanks, A.L., Mattner, S.W., and Porter, I.J. (2006). Methyl bromide alternatives for horticulture - Research publications CD-ROM. ISBN 1 74146 712 8.

Conference Papers:

Gounder, RK, Mattner, SW, Porter, IJ, Shanks, AL, Wren, DJ, and Allen, D (2005). The impact of biofumigants on pathogens of strawberry. Proceedings of the 15th Australasian Plant Pathology Conference, p 176.

Gounder, RK, Mattner, SW, Mann, RC. Trinder, LE, and Porter, IJ (2007). Isolation of plant-growth promoting bacteria from fumigated soils. Proceedings of the 16th Australasian Plant Pathology Conference, p 127.

Horner, I.J. 2006. Summary of alternative fumigant trials in New Zealand strawberries, 1998-2006. Annual International MBAO Conference, p 60:1-4

Mann, R.C., Mattner, S.W., Gounder, R.K., and I.J. Porter (2007). Drip fumigation of iodomethane in the Australian protected horticulture industry. Annual International MBAO Conference, p 122:1-4.

Mann, RC, Mattner, SW, Gounder, RK, and Porter IJ (2005). Evaluating novel soil fumigants for Australian horticulture. Annual International MBAO Conference, p 34 1-4.

Mann, R.C., Mattner, S.W., Gounder, R.K., and I.J. Porter. 2007. Iodomethane offers opportunities for methyl bromide phase out and soil disinfestations in Australia. Annual International MBAO Conference, p 77:1-4.

Mann, RC, Mattner, SW, Gounder, RK, and Porter IJ (2007). Novel application of soil fumigants in protected horticulture. Proceedings of the 16th Australasian Plant Pathology Conference, p 112.

Mann, RC, Mattner, SW, Gounder, RK, Porter, IJ, and Allen, D (2005). Movement and efficacy of iodomethane in Australian soils. Proceedings of the 15th Australasian Plant Pathology Conference, p325.

Mattner, S.W. (2006). Biofumigantes: La rotación beneficiosa para fresas. [Biofumigants: Beneficial rotations for strawberries]. CD-Rom. *In* Taller Internacional: Nuevas alternativas al uso de bromuro de metilo en fresa (fruta y estolones). May 2006. Baja California, Mexico.

Mattner, S.W. (2006). Producción de fresa en viveros con alternativa al uso de bromuro de metilo (caso Australia) [Production of strawberry runners with alternatives to the use of methyl bromide (case Australia)]. CD-Rom. *In* Taller Internacional: Nuevas alternativas al uso de bromuro de metilo en fresa (fruta y estolones). May 2006. Baja California, Mexico.

Mattner, S.W., Gounder, R.K., Mann, R.C., Trinder, L.E., and I.J. Porter (2007). Isolation of plant-growth promoting bacteria from fumigated soils. Annual International MBAO Conference p 124:1-4.

Mattner, S.W., Porter, I.J., Gounder, R.K., and Mann, R.C. (2007). Factors that impact on the ability of biofumigants to suppress fungal pathogens and weeds of strawberry. Proceedings of the 6th North American Strawberry Symposium. Ventura, USA. p 19.

Mattner, S.W., Porter, I.J., Gounder, R.K., Mann, R.C.., and Fraser, P. (2007). Phase-out and emission control of methyl bromide in the Australian strawberry industry. Proceedings of the 6th North American Strawberry Symposium. Ventura, USA. p 9.

Mattner, S.W., Wite, D.A., Baxter, G.G., Hayes, G.A., Mann, R.C., and I.J. Porter (2007). Disinfestation of expanded-polystyrene seedling trays in the Australian tobacco industry. Annual International MBAO Conference, p 82:1-4.

Mattner, S.W., Wite, D.A., Baxter, G.G., Holmes, R.J., Hayes, G.A., and I.J. Porter. 2007. Integrated disinfestations of EPS-trays using washing practices and solarization. Annual International MBAO Conference, p 125:1-4.

Porter I., Banks J., Andersen S., Mattner S., and Fraser, P. (2007). Phase out of methyl bromide: implications for the ozonelayer, bioprotection, biosecurity and climate change. Proceedings of the 16th Australasian Plant Pathology Conference, p 100.

Porter, IJ, Mattner, SW, Brett, RW (2005). Methyl bromide phaseout - the impact on plant protection and international biosecurity. Proceedings of the 15th Australasian Plant Pathology Conference, p 218.

Porter, I.J., Trinder, L.E., Partington, D., Mattner, S.W., Karavarsamis, N., and Hannah, M. (2006). Soil disinfestation treatments: What has replaced methyl bromdie and are industries and scientists getting it right? Proceedings of the 4th Australasian Soilborne Diseases Symposium, Queenstown, New Zealand. p 35-36.

Tostovrsnik, NS, Shanks, AL, Porter, IJ, Mattner, SW and Brett, RW (2005). Facilitating the adoption of alternatives to methyl bromide in Australian horticulture. Proceedings of the 15th Australasian Plant Pathology Conference, p 192.

Tostovrsnik, NS, Shanks, AL, Porter, IJ, Mattner, SW and Brett, RW (2005). Facilitating the adoption of alternatives to methyl bromide in Australian horticulture. Annual International MBAO Conference, p 13: 1-4.

Wite, D., Mattner, SW, Baxter, GG, Holmes, RJ, Hayes, GA and Porter, IJ (2007). Soalrisaiton of expanded-polystyrene seedling trays in the former Australin tobacco industry. Proceedings of the 16th Australasian Plant Pathology Conference, p 126.

Industry Reports:

I.J. Horner. 2005. Sustainable Strawberry Soil Management Without Methyl Bromide. Quarterly Research Report No.3 for Strawberry Growers NZ Inc. HortResearch Client Report No. 15052. HortResearch Contract No. 19427. April 2005.

I.J. Horner, E.H. Bigwood, S. Mattner, R. Gounder, A. Pearson. 2005. Sustainable Strawberry Soil Management Without Methyl Bromide. Quarterly Research Report No.4 for Strawberry Growers NZ Inc. HortResearch Client Report No. 15071. HortResearch Contract No. 19427. June 2005.

Horner IJ. Sept 2005. Sustainable strawberry soil management without methyl bromide. Quarterly Research Report No.5 for Strawberry Growers NZ Inc. HortResearch Client Report No. . HortResearch Contract No. 19427.

Horner IJ. Dec 2005. Sustainable strawberry soil management without methyl bromide. Quarterly Research Report No.6 for Strawberry Growers NZ Inc. HortResearch Client Report No. . HortResearch Contract No. 19427.

Horner IJ. March 2006. Sustainable strawberry soil management without methyl bromide. Quarterly Research Report No.7 for Strawberry Growers NZ Inc. HortResearch Client Report No. 15057. HortResearch Contract No. 19427.

Horner IJ, Gounder R, Mattner S, Bigwood EH, Taylor T. June 2006. Sustainable strawberry soil management without methyl bromide. Quarterly research report no. 8 for Strawberry Growers NZ Inc. HortResearch Client Report No. 15073. HortResearch Contract No. 19427.

Horner I. September 2006. Sustainable strawberry soil management without methyl bromide. Quarterly research report no. 9 for Strawberry Growers NZ Inc. HortResearch Client Report No. 15059, HortResearch Contract No. 19427.

Horner I. February 2007. Sustainable strawberry soil management without methyl bromide. Progress report for Sustainable Farming Fund project number 04/145. HortResearch Contract No. 19427.

Horner IJ, Gounder R, Mattner S, Taylor TJ. June 2007. Sustainable strawberry soil management without methyl bromide. Final research report for Strawberry Growers NZ Inc. HortResearch Client Report No. 15063. HortResearch Contract No. 19427.

Mattner, S.W., Porter, I.J., and Fraser, P. (2006). Emission reduction strategies - strawberry runners. Report to UN MB Technical Options Committee.

Grower Newsletter Articles:

Horner, I.J. 2005. Soil Management without Methyl Bromide. Strawberry Growers New Zealand Inc. Newsletter, March 2005.

Horner, I.J. 2005. Soil Fumigation. Article in SGNZ newsletter, Nov.2005.

Horner, I.J. 2006. Sustainable soil management without methyl bromide. SGNZ Newsletter, March 2006.

Horner ,I.J. 2006. Sustainable strawberry soil management without methyl bromide. Summary for MAF Sustainable Farming Fund website.

Horner, I.J. 2006. VIF mulches. SGNZ Newsletter, November 2006.

Horner I.J. 2007. Soil Fumigation Update. Special flyer sent to all NZ strawberry growers, January 2007.

Horner, I.J. 2007. Soil fumigation update. SGNZ Newsletter, May 2007.

Hutton, D., Gomez, A., and Mattner, S.W. (2006) Plant pathology. QDPI Strawberry R&D Update, p 16-20.

Mann, R.C., and Mattner, S.W. (2006). Methyl iodide registration on its way. VicStrawberries, Issue 24, p3.

Mattner, S.W. (2006). Breaking the critical-use barriers preventing Australian horticulture from phasing out methyl bromide. Strawberries Australia Annual Report.

Mattner, S.W. (2007). Breaking the critical-use barriers preventing Australian horticulture from phasing out methyl bromide. Strawberries Australia Annual Report.

Mattner, S.W. (2008). Breaking the critical-use barriers preventing Australian horticulture from phasing out methyl bromide. Strawberries Australia Annual Report.

Mattner, S.W. (2006). Phasing out methyl bromide. Wild About Strawberries, Issue 12, p2.

Mattner, SW (2005). New strawberry research commences. VicStrawberries Newsletter, Issue 17, p 2.

Mattner, S.W. and Porter, I.J. (2006). MB Research and Communication Update. Wild About Strawberrries, Issue 11, p 5.

Mattner, S.W., Shanks, A.S. and Porter, I.J. (2006). Growers participate in fumigant workshop. VicStrawberries, Autumn, p 3.

Thomson, C., Mattner, S.W. and Shanks, A.S. (2006). Growers participate in fumigant workshop in Victoria. Wild About Strawberries Issue 11, p 6.

7.4 Communication Activities

- Horner IJ. June 2005. Sustainable strawberry soil management without methyl bromide. Presentation at Strawberry Growers New Zealand Annual Research Seminars, Auckland.

- Berry Industry Expo, Lilydale, Vic, 9 June 2005 (oral presentations and information booth on MB alternatives presented to *c.* 80 growers)

- Strawberry runner growing and methyl bromide - the way forward, Knoxfield 3 August 2005 (2 oral presentations to representatives of strawberries Australia, strawberry nursery growers, Department of Environment and Heritage, and Horticulture Australia)

- Tobacco Industry Advisory Committee Meeting, Myrtleford, Vic, 9 September 2005.

- WA strawberry growers field day, Wanneroo, 9 October, 2005 (updated 18 strawberry fruit growers on new fumigant and non-fumigant alternatives to MB, demonstrated grower trials of plug plants)

- United Nations Methyl Bromide Technical Options Committee field day, 29 August, 2005 (grower meeting and tour of the Toolangi strawberry runner growing district by international delegates from the UN, and Environment Australia)

- Strawberries Australia meeting, Lenswood SA, 8 October 2005 (oral presentation to representatives of Strawberries Australia)

- Strawberry runner industry meeting, 'strategies to achieve total MB phase-out', Tuesday 7th February 2006, DPI Knoxfield Centre - stakeholder meeting with the strawberry runner industry to discuss strategies for making the transition from a critical use exemption to phase out of MB

- Tobacco Industry Advisory Committee Meeting, Myrtleford, Vic, 21 March 2006.

- Victorian strawberry fruit industry field day, 'chemical and non-chemical approaches to soil management - demonstrating fumigants and biofumigants in the field', Friday 7th April 2006, Millgrove, Victoria - attended by 65 growers and industry stakeholders.

- Presentation and participation at the DEWHA strawberry runner CUE meeting attended by Strawberries Australia, Queensland runner industry, TCSRGC, VSICA, Department of Environment, Water, Heritage and the Arts, Chemical Standards Victoria, APVMA, QDPI&F, Agricultural Development (DPI Vic), and EPA Victoria. Tullamarine, Victoria, 19 June 2006.

- Horner IJ. July 2006. Sustainable strawberry soil management without methyl bromide. Presentation at Strawberry Growers New Zealand Annual Research Seminars, Auckland.

- Horner, IJ 2007. Soil Fumigation Workshop for Strawberry Growers. Massey, Auckland, 8th Feb. 2007

- Horner, IJ 2007. Soil Fumigation Workshop for Strawberry Growers. Hamilton, 9th Feb. 2007

- Guest lectures, 'The strawberry industry in Australia and the program to replace methyl bromide'. Universidad Nacional Autonoma de Mexico and Universidad Autonoma Chapingo Mexico. 19-20 February 2007.

- VSICA presentation, 'Efficacy of methyl iodide for strawberry runner production'. Wandin, 28 March 2007.

- Horner IJ. June 2007. Sustainable strawberry soil management without methyl bromide. Presentation at strawberry growers New Zealand Annual Research Seminars, Auckland.

- Presentation and Information Booth, 'Alternative fumigants and soil treatments', Berry Industry Expo. Lilydale, 7 June 2007.

8 Recommendations

In 2008, strawberry runners are the only Australian horticultural industry still applying for critical-use exemptions to retain MB. During the course of this project, an independent review and facilitated meetings were conducted with industry, government and stakeholders to identify the barriers preventing the strawberry runner industry from adopting alternatives. Additionally, these meetings identified the research and communication activities still required to assist the industry in moving towards alternative systems. The following issues need to be addressed for MB phase out to progress:

(1) A review of the certification regulations for strawberry runners and the need for federal and state government involvement and understanding of the importance that these regulations have for national biosecurity.
(2) An analysis of the risk to plant health involved with changing strawberry certification guidelines to accept MB alternatives; and agreement on the relative accountabilities of industry, government, and chemical companies for possible future litigation.
(3) Quantification of the pathogen threshold levels in strawberry runners that meet current certification standards with MB; and comparative studies of pathogen levels under alternative systems (particularly methyl iodide).
(4) Clearer definitions of the quality standards and practices that allow market access and trade of certified runners between Australian states.
(5) Commercial trials of methyl iodide to support current registration applications to the APVMA; and an understanding of the commercialisation, distribution and stewardship processes needed before adoption by industry could commence.
(6) Importation of new fumigant alternatives into Australia (such as dimethyl disulphide) as a contingency in the event that methyl iodide fails to meet registration, certification or economic constraints; and identification of commercial partners that would take responsibility for registering these products.
(7) Research on minimum doses and emission controls for MB to allow reduced amounts being applied for in future critical-use nominations; and identification of the role of government and industry in leading registration applications for these measures to the APVMA.
(8) Economic assessments of alternative systems and the impacts this will have on profits in the strawberry runner and fruit industries, and the likelihood of cost increases being borne by retailers and consumers.
(9) Development of funding scenarios that take a balanced approach to the public good and industry outcomes of future R,D&E.

9 References

BS98004. Mattner S.W. et al. (2002). *Best practice cropping strategies as alternatives to pre-plant soil disinfestation with methyl bromide for temperate strawberry fruit and runner production.* HAL Final Report BS98004. Sydney, Australia.

BS01004. Mattner, S.W. et al. (2005). *Identification of sustainable soil disinfestation options for the temperature Australian strawberry industry*. HAL Final Report BS98004. Sydney, Australia.

BS04005. Mattner, S.W. et al. (2006). *Understanding the relevance of soil health for sustained strawberry production*. HAL Final Report BS04005. Sydney, Australia.

Desmacheliar, J. (1998). *Determination of effective fumigant concentrations in different soil types for methyl bromide and other soil fumigants*. Rural Industries Research and Development Corporation Report, Canberra, Australia.

Durner, et al. (2002). Recent advances in strawberry plug transplant technology. *HortTechnolgy* **12**: 545-550.

Fennimore, S. et al. (1999) Weed control in California strawberries without methyl bromide. *International MBAO Conference* 12: 1-4.

HG01005. Shanks, A.L. et al. (2006). *Facilitating national adoption of methyl bromide alternatives*. HAL Final Report HG01005. Sydney, Australia.

HG01045. Brett, R.W. et al (2005). *Preparing for methyl bromide phase-out in Australian glasshouse industries*. HAL Final Report HG01045. Sydney, Australia.

HG04018. Mann, R.C. et al. (2008). *Evaluation of methyl iodide for soil disinfestation in Australian Horticulture. Part II.* HAL Final Report HG04018. Sydney, Australia.

Mattner, S.W. et al. (2003). Strawberry plug plants in perspective. CD-Rom. *In* Proceedings of the 1st Trans-Tasman Berryfruit Conference. July 2003. Auckland, NZ.

TB04001. Baxter, G.G. et al. (2007). *Sustainable tobacco production.* HAL Final Report TB04001. Sydney, Australia.

Zebrowska, J.I et al. (2003). Suitability of strawberry (Fragaria x ananassa) microplants to the field cultivation. *Food, Agriculture and Environment* **1**: 190-193.