Horticulture Innovation Australia

Final Report

Development of soil disinfestation systems for production of certified strawberry runners

Victorian Strawberry Industry Certification Authority

Project Number: BS13000

BS13000

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1. Summary

The withdrawal of the soil fumigant methyl bromide (MB) is currently threatening the integrity of the Victorian Runner Certification Scheme and the viability of the Australian strawberry industry. The use of mixtures of MB and chloropicrin (Pic) for soil disinfestation in the runner industry has been world's best practice, but non-quarantine uses are being phased-out under the *Montreal Protocol*. Soil disinfestation with MB/Pic has enabled the production of healthy runners and protected the strawberry fruit industry against the spread of soil-borne pathogens, weeds, and pests. It has therefore secured the productivity and viability of the industry.

Currently available substitute fumigants to MB/Pic (e.g. 1,3-dichloropropene (1,3-D)/Pic, 65:35) do not work in the unique soil type (high clay and organic matter) and environment (cold temperatures) at Toolangi, Victoria, which is the major district for production of runners in Australia. The soils in this region retain residues of substitute fumigants, which can kill strawberry plants (crop phytotoxicity). Without an effective substitute or access to MB in the runner industry, evidence suggests that strawberry fruit yields across Australia will decrease by 15%, and plant health will decline.

This project aimed to develop soil-less and soil disinfestation systems to replace MB/Pic for the production of Certified strawberry runners.

Partial budget analysis showed that the use of soil-less substrates for runner production in Victoria would increase the cost of transplants by 6-fold, compared with production in MB/Pic-treated soil. Research showed that hydroponic systems increased the efficiency of transplant production, compared with soil-less substrates. However, fruit yields from transplants produced using hydroponics and soil-less media (plug plants) were highly variable across Australia (40% less to 22% more), and require further research on their physiology before being a technically or economically feasible method of production.

Research identified strategies for the runner industry to reduce the risk of crop phytotoxicity from substitute fumigants. This includes the use of formulations of 1,3-D/Pic containing low concentrations of 1,3-D (i.e. 1,3-D/Pic (20:80)), and new substitute fumigants (e.g. ethanedinitrile (EDN) and dimethyl disulphide/Pic) with short residual times in soils at Toolangi, Victoria. Co-application of these substitute fumigants with specific pre- and post-emergent herbicides (isoxaben, phenmedipham and fluazifop-p) improved weed control, without affecting runner yields. Data from this project supported the registration of a new formulation of 1,3-D/Pic (20:80) (TriForm 80®). However, other products (except fluazifop-p) are still undergoing evaluation for registration in Australia, and are not currently available to runner growers.

None of the substitute fumigants tested provided the same level of control of soil-borne pathogens as MB/Pic, particularly at greater soil depths. Runners grown in soils treated with substitute fumigants in the nursery, produced 16% less fruit and had higher incidences of some diseases (Pythium rot) in the fruit industry, compared with runners grown in the nursery in soils treated with MB/Pic. Further research is urgently needed to improve pathogen control using key substitute fumigants, including evaluation of: deeper application, different fumigant formulations, use of totally impermeable films, higher application rates, new fumigants, and integration with biofumigation rotations.

The runner industry needs to consider making further applications to the United Nations for critical-use exemptions to retain MB, while research and registration of key substitute fumigants continues. In addition, governments need to consider whether the current use of MB in the runner industry to control and prevent the spread of major soil-borne pathogens around Australia qualifies as a quarantine use, which is exempt from phase-out. These strategies would enable time to develop viable substitutes to MB, and protect the fruit industry from expected losses of $60 M p.a. without MB or a suitable substitute in the runner industry.

2. Keywords

Strawberry; Strawberry nursery; Fumigant; Methyl Bromide; Herbicide; Fungicide; Soil-less Production; Plug Plant; Critical-use Exemption; Quarantine.

3. Introduction

Certified planting material (runners) derived from pathogen-tested (PT) stock underpins the national strawberry fruit industry valued at $450 M p.a. (Strawberries Australia, 2012). The Victorian runner industry produces about 70% (60 million runners) of the planting material used by the Australian strawberry fruit industry. The initiation of the Victorian Strawberry Runner Certification Scheme in the 1960s immediately quadrupled fruit yields and allowed the strawberry fruit industry to develop and flourish (Anon., 2010). High health planting material based on the PT concept remains the cornerstone of a productive and profitable national fruit industry.

Soil disinfestation is the process of reducing or eliminating pathogens, weeds and pests in soil prior to planting crops. It is the key strategy used in the Certification Scheme to safeguard against the build up of soil-borne pests, and their possible spread to the fruit industry in runners. The use of mixtures of methyl bromide (MB) and chloropicrin (Pic) to disinfest soil for runner production was world's best-practice, but non-quarantine uses of MB are being phased-out under the *Montreal Protocol*. This is because MB is reported to be an ozone-depleting product (Porter et al., 2009). The withdrawal of MB is threatening the integrity of the Certification Scheme, and the viability of the Australian strawberry industry.

In the USA, federal legislation has classified soil disinfestation with MB/Pic in the runner industry as a quarantine use, which is exempt from phase-out. This is to prevent the possible distribution of nematode pathogens across county, state, and international borders. The classification of MB as a quarantine treatment has secured unlimited use of the product in the runner industry in the USA, safeguarded the high-health status of its fruit industry, and allowed industry expansion. Its use in the USA also supports the health of runners exported to some European countries. In Australia, soil disinfestation with MB/Pic in the runner industry is not currently classified as a quarantine use and is therefore not exempt from phase-out.

Over the last 20 years, extensive research programs have successfully identified and developed substitute fumigants, such as 1,3-dichloropropene (1,3-D) and Pic, to replace the use of MB/Pic for soil disinfestation in Australian horticulture, including the strawberry fruit industry (BS98004, BS01004, BS04009, BS07014). These substitutes, however, did not work effectively in the strawberry runner industry. The problem related to the unique soil type (high clay and organic matter content) and environment (cold temperatures) at Toolangi, Victoria, which is the major district for production of runners in Australia. In commercial trials, the soils at Toolangi consistently retained residues of substitute fumigants and caused crop losses of up to 40% due to phytotoxicity, and poor control of soil-borne pathogens, weeds, and pests. The seriousness of the issue is highlighted by the fact that the previous runner industry at Kempton, Tasmania closed down in 2014 because the substitute fumigants it adopted failed to control soil-borne pests to adequate levels (P. Bignell, personal communication). Without access to MB or an effective substitute, evidence suggested that supply of runners to the fruit industry in Australia would fall by up to 30%, fruit yields would decrease by 15% (worth $30-60 M p.a.), and plant health would decline (BS01004).

To overcome this, the runner industry has applied annually for critical-use-exemptions (CUEs) from the United Nations (UN) to retain the use of small quantities of MB (29.76 tonnes) for soil disinfestation and production of Certified runners, until a suitable substitute is found. Extensive research that showed there were no technically or economically feasible substitutes (BS98004, BS01004, BS04009, BS07014) provided the basis for these applications. CUEs, however, are only a short-term solution for the runner industry, and it is unlikely that the UN will grant them for long periods into the future.

The aim of this project was to identify substitute treatments to MB/Pic for soil disinfestation that meet Certification and biosecurity standards for strawberry runners. The approach was to: (1) develop integrated treatments from existing and new chemistries (fumigants, biofumigants, herbicides, fungicides) that disinfest soils at Toolangi, Victoria without causing runner crop losses from phytotoxicity, and (2) evaluate soil-less systems for runner production that avoid the need for soil disinfestation.

4. Methodology

4.1 General Approach:

This project conducted field trials and analysis in the Victorian strawberry nursery industry, and evaluation trials in the Victorian and Western Australian strawberry fruit industries on soil disinfestation and soil-less systems to replace the use of MB/Pic for runner production. Field days were regularly held at trial sites to communicate research outcomes to growers.

A steering group was formed at the beginning of the project to guide the direction of the research and communication activities, and ensure they remained relevant to industry and government needs. This approach was necessary to allow flexibility in response to directions requested by the United Nation's MB Technical Options Committee (MBTOC), and to ensure that research focused on practical methods suitable for rapid adoption by industry. The steering group met annually, and consisted of representatives from the strawberry runner and fruit industries, Victorian Strawberry Industry Certification Authority, Commonwealth Department of the Environment, commercial fumigators, Victorian Department of Primary Industries, La Trobe University, and project researchers. The group reviewed progress within the project and developed annual work plans, which were then submitted to HIA Limited for endorsement.

4.2 Development of Integrated Soil Disinfestation Systems:

4.2.1 Small-Scale Trials

Six field trials were conducted at Toolangi, Victoria from 2013 to 2017 investigating the effects of 102 different combinations, rates, and application methods of fumigants (Table 1), and biofumigant, pre- and post-emergent herbicides, and fungicides (Table 2) on soil disinfestation and strawberry runner production. The selection of these treatment combinations was based on reports of their successful use in strawberries in the literature (e.g. Fennimore and Richard, 1999; Jennings et al., 2006) and those used overseas (as seen on study tours, see below). Field trials were conducted as randomised split-plot designs with four blocks. Fumigant treatments formed the main plots (30-70 m × 2.7 m), and biofumigant, herbicide and fungicide treatments formed the split-plots (10-20 m × 2.7 m). Untreated and MB/Pic-treated (500 kg/ha) soils were used as the controls. Data were analysed using ANOVA as performed on Genstat v.16. Appropriate data transformations were made when necessary to restore normality of distribution and/or homogeneity of variance.

Fumigant treatments were applied to clay ferrosol soils under barrier films in September/October using the methods described in Table 1. Licensed contractors applied all fumigants in the trials. Barrier films were removed after 1-2 weeks, and the soil allowed to air for 4-8 weeks after treatment (to meet recommended plant-back times). Single rows of strawberry mother plants were transplanted along the middle of the plots, spaced 50 cm apart. Herbicides and fungicides were applied using a knapsack sprayer (Solo® 12 volt) as described in Table 2. All other agronomic procedures followed standard industry practices. Runners were harvested in May/June the following year. The strawberry cultivars used in the trials included Albion, Monterey, San Andreas, Gaviota and Fortuna.

Table 1. *List of fumigant and barrier film treatments investigated in different combinations in trials in the strawberry runner industry at Toolangi, Victoria from 2013-2017.*

Active Ingredient	Commercial Name	Abbreviation	Rate	Application Method
Fumigants				
chloropicrin	PicPlus®	Pic	340 kg/ha	Shank injection under barrier film
1,3-dichloropropene / chloropicrin (65:35)	Telone C-35®	1,3-D/Pic (65:35)	600 kg/ha	Shank injection under barrier film
1,3-dichloropropene / chloropicrin (40:60)	TriForm 60®	1,3-D/Pic (40:60)	450 kg/ha	Shank injection under barrier film
1,3-dichloropropene / chloropicrin (20:80)	TriForm 80®	1,3-D/Pic (20:80)	400 kg/ha	Shank injection under barrier film
cyanogen	EDN Sterigas®	EDN	500 kg/ha	Shank injection under barrier film
dimethyl disulphide	Paladin®	DMDS	500 kg/ha	Shank injection under TIF
dimethyl disulphide / chloropicrin (79:21)	Paladin 79/21®	DMDS/Pic	600 kg/ha	Shank injection under TIF
metham sodium	Metham®	MS	250 L/ha 500 L/ha	Spade injection under rolling and barrier film
dazomet	Basamid®	Daz	350 kg/ha	Gandy® application and rotary hoe incorporation under barrier film
methyl bromide / chloropicrin (50:50)	Chlorofume 500-500®	MB/Pic	500 kg/ha 400 kg/ha	Shank injection under barrier film
Barrier Films				
low density polyethylene	LDPE	LDPE	-	Plastic layer on fumigation rig
LDPE / polyamide laminate	Guardian® virtually impermeable film	VIF	-	Plastic layer on fumigation rig
LDPE / ethylene vinyl alcohol laminate	VaporSafe® totally impermeable film	TIF	-	Plastic layer on fumigation rig

Table 2. *List of biofumigant, herbicide and fungicide treatments investigated in different combinations in trials in the strawberry runner industry at Toolangi, Victoria from 2013-2016.*

Active Ingredient	Commercial Name	Rate	Application Method
Biofumigant			
allyl isothiocyanate	Voom®	500 L/ha	Applied as a diluted drench (15%), and rotary incorporated under barrier film at fumigation.
Pre-Emergent Herbicides			
isoxaben	Gallery®	333 g/ha	Sprayed over soil after planting in recommended volumes of water.
napropamide	Devrinol®	6.7 kg/ha	Sprayed over soil after planting in recommended volumes of water.
metolachlor	Dual Gold®	2 L/ha	Sprayed over soil after planting in recommended volumes of water.
terbacil	Sinbar®	4 L/ha	Sprayed over soil after planting in recommended volumes of water.
oxyfluorfen	Goal®	4 L/ha	Sprayed over soil after planting in recommended volumes of water.
Chlorthal-dimethyl	Dacthal®	11 kg/ha	Sprayed over soil after planting in recommended volumes of water.
clopyralid	Lontrel®	4 L/ha	Sprayed over soil after planting in recommended volumes of water.
α-pinene	BioWeed®	60 L/ha	Sprayed over soil after planting in recommended volumes of water.
Post-Emergent Herbicides			
fluazifop-p	Fusliade®	1.65 L/ha	Spayed over the crop and soil on a fortnightly basis in recommended volumes of water.
phenmedipham	Betanal®	5.5 L/ha	Spayed over the crop and soil on a fortnightly basis in recommended volumes of water.
Fungicides			
fosetyl-Al	Aliette®	4.6 kg/ha	Applied as a drench at planting and then sprayed over the crop and soil every 6 weeks in recommended volumes of water.
thiophanate methyl / etridiazole	Banrot®	40 kg/ha	Applied as a drench at planting in recommended volumes of water.

In 2014/15, a separate trial was established using the modelling method described by Mattner et al. (2003) to determine plant-back times (period required between fumigation and planting) of key substitute fumigants (1,3-D/Pic 35:65, 40:60 and 20:80, Pic, Pic + MS, DMDS, and DMDS/Pic) compared with MB/Pic, and their risk of causing crop losses due to phytotoxicity. Following fumigation (see above), mother plants were transplanted into soil at 2, 4, 6, 8, or 12 weeks after treatment. The trial was conducted as a randomised split-plot design with four blocks. Fumigant treatments formed the main plots and plant-back treatments formed the split-plots. The strawberry cultivar used was Gaviota, because it has previously shown sensitivity to fumigant residues in soil (Mattner et al., 2003).

Parameters assessed in the trials were measured using established techniques (BS07014), and included: (1) fumigant concentration and distribution in soil (using photo-ionisation detection (MiniRae®) and/or detector tubes (Gastec®), Van Wambeke, 2010); (2) survival of buried inoculum (sclerotia or inoculated seed) of strawberry pathogens or weed seeds; (3) pathogen concentration in soil (qPCR for a suite of strawberry pathogens conducted by the South Australian Research and Development Institute (*Pythium* spp. clade I & F, *Verticillium dahliae*, *Meloidogyne hapla*, *Pratylenchus penetrans*, and *Macrophomina phaseolina*); (4) weed emergence (number and identity per m²); (5) mother plant establishment (length of primary stolon, leaf number, leaf area at two months after planting); (6) crown and root diseases/syndromes in harvested runners (e.g. incidence of Phytophthora crown rot and severity of black roots); and (7) runner yield (runners/m²) and quality (crown diameter).

4.2.2 Commercial Trials

From 2013-2017, the best soil disinfestation systems (Pic and 1,3-D/Pic (60:40) and (20:80) + isoxaben) identified in small-scale trials (see above) were investigated in five commercial trials in the runner industry, compared with MB/Pic. Plot areas were c. 0.5 – 1 ha per treatment and planted with the same strawberry cultivar (either Palomar, Monterey, Albion, or Fortuna). Similar parameters were measured in commercial trials to those described above. In addition, runners harvested from different treatments were planted in the strawberry fruit industry at Millgrove, Victoria and Wanneroo, Western Australia. These trials were set up as randomised complete block designs, with four blocks. There were 20-32 plants per plot. Yields of fruit were assessed through the season, and revenue from fruit calculated using national market data (supplied by FreshLogic).

4.3 Soil-less Systems for Production of Strawberry Runners:

4.3.1 Feasibility Analyses

A literature review and partial-budget analysis were conducted to investigate the technical and economic feasibility of soil-less systems for production of runners, which avoid the need for soil disinfestation. The partial-budget analysis followed the methods established by the UN's Technical and Economic Assessment Panel (TEAP) for the economic analysis of substitutes to MB (UNEP, 2013). The analysis calculated the projected price of bare-rooted runners grown in substrate bins for strawberry fruit growers, compared with those grown in MB/Pic-treated soils. TEAP states that 'alternatives leading to decreases in gross margins of around 15 to 20 percent or more are not financially feasible', and this formed the benchmark for assessing the economics of the system. The literature review and partial-budget analysis were published as peer-reviewed papers (Mattner et al., 2014; 2016, see 'Scientific Refereed Publications').

4.3.2 Study Tours

This project organised and conducted study tours of the Japanese (2013), European (2014) and South African (2015) runner industries, which have partially adopted soil-less production systems. Representatives of the Victorian runner industry and VSICA participated in the study tours. Outcomes from the tours were communicated to the runner industry in technical reports, grower presentations, and the literature review (see above). Design aspects of the soil-less systems observed overseas were incorporated and evaluated in research in Australia (see below).

4.3.3 Research on Soil-less Systems

Three trials were conducted at Toolangi, Victoria in and near a commercial screenhouse facility from 2013 - 2016. The screenhouse was 800 m^2 with a concrete floor, double annex door entrances, single-skin plastic film on the roof, and Biomesh (opening size of 0.24 mm × 0.75 mm) on the sides for natural ventilation. Three soil-less production systems were evaluated for production of strawberry transplants: (1) hydroponics outdoors (2) hydroponics in the screenhouse, and (3) production in bins containing substrate in the screenhouse. Yields of transplants in the soil-less systems were compared with the standard production method in the field in a soil fumigated with MB/Pic (500 kg/ha). All plants in soil-less treatments were fertigated with a standard hydroponics blend and drip irrigated using established practices (BS06029, BS09019). The cultivars used in the trial were San Andreas, Albion, and Monterey (day-neutral cultivars), and Festival and Camarosa (short-day cultivars). The trials were planted in September / October and harvested in April / May.

The hydroponic system consisted of polyethylene bags (100 cm × 20 cm × 15 cm) containing a soil-less mix (Coco-peat, pH of 5.7 – 6.5) mounted on raised gutters (2.1 m). Strawberry mother plants (produced by vegetative propagation) were planted in a single row 20 cm apart in the bags. Strawberry stolons produced from the mother plants were allowed to hang down from the raised gutters. At harvest, tips (stolon nodes) were planted into seedling containers (166 cm^3 cells) filled with substrate (Debco Seed and Cutting Mix). Seedlings were misted for 4-weeks in a screenhouse to produce strawberry plug plants.

The substrate bin treatment consisted of plastic bins (1 m × 1 m × 0.5 m) filled with a soil-less mix (70:30 coir/composted bark mixture). A single mother plant (produced by vegetative propagation) was planted in each bin. Nodes produced on stolons were pinned into the substrate to produce bare-rooted runners.

Yields of transplants (plug plants or bare-rooted runners, depending on the treatment) were expressed on an area of production basis (transplants/m^2). There were 10 replicates for each treatment. Results were compared using Student's t-test, and 95% confidence intervals calculated using Genstat v.16.

The performance of plug plants was evaluated in the Victorian nursery industry at Toolangi, Victoria and the strawberry fruit industry at Millgrove, Victoria and Wanneroo, Western Australia, compared with bare-rooted runners produced in MB/Pic-treated soil. The trials were conducted as randomised complete block or split-plot designs, with four blocks. Runner or fruit yields were determined through the season.

4.4 Technology Transfer:

A technology transfer program was conducted to communicate project outcomes to a diverse audience.

4.4.1 Government Agencies

Critical-use nominations for MB were prepared annually (three in total) for the runner industry based on research in this project, and delivered to the Commonwealth Department of the Environment and the United Nations for consideration. An analytical report was also prepared for industry to allow an assessment on the quarantine status of MB use in the runner industry by state and national biosecurity agencies.

4.4.2 Strawberry Growers

Field demonstrations and workshops were conducted annually for runner growers at trial sites. Additionally, growers were informed of project outcomes through articles in industry magazines and newsletters (see 'Outputs'). At the completion of the project, a best-practice guide on soil disinfestation was produced and distributed to all Victorian runner growers (Appendix I).

A small desktop study was conducted to explore the possibility of moving the runner industry from Toolangi to other areas in Australia that may have soil types more suitable for the use of substitute fumigants. This analysis considered previous research trials on runners in different regions, data on soil type, late summer / autumn temperatures for chill, altitude, and plant protection regulations. Methodology also included personal communication and meetings with agronomists and government scientists in different regions of Australia, and with runner growers themselves. The analysis did not consider the economics and social impact of moving the runner industry to other regions of Australia. The analysis was delivered to the Victorian runner industry.

4.4.3 Chemical Companies

Reports on the technical efficacy of individual products were prepared and used by chemical companies to support the possible registration of these products (see 'Outputs'). Trial inspections were held for representatives from chemical companies.

4.4.4 Scientific Community

Scientific outcomes from this project were published in peer reviewed papers (see 'Scientific Refereed Publications') and conference papers (see 'Outputs').

5. Outputs

5.1 Field Days, Workshops, Demonstrations, Meetings and Presentations:

Merriman PR et al. (2013). 10 July 2013. Critical use exemptions and MB alternatives (field day with representatives of the Department of the Environment, and strawberry runner and fruit growers). Toolangi Research Farm, Victoria. 10 July 2013. 17 Attendees.

Milinkovic M. et al. (2013). MB Research Update and Soil-less Systems of Runner Production (oral presentations). Toolangi Research Farm, Victoria. 13 November 2013. 21 Attendees.

Weda G. et al. (2013). Guest Strawberry Fruit Grower Talk: Dr Doug Shaw UC Davis, 'The Importance of Methyl Bromide for Strawberry Production' (field day and workshop). Millgrove, Victoria. 29 November, 2013. 41 Attendees.

Mattner SW (2014). Drip fumigation with alternative fumigants in the strawberry fruit industry (oral presentation at field day translated into Vietnamese). Strawberry Growers Association of Western Australia, Wanneroo, Western Australia. 27 February 2014. 29 Attendees.

Mattner SW et al. (2014). (1) European systems of runner production, (2) North Carolina program on MB alternatives (Dr Robert Welker, guest speaker), (3) MB research update, (4) Field trial inspection (field day and farm walk). Toolangi Research Farm. 10 March 2014. 8 Attendees.

Merriman PR et al. (2014). Meeting with the Victorian Minister of Agriculture. Presentation, 'MB and quarantine in the strawberry runner industry', and trial inspection. Toolangi Research Farm, Victoria. 20 March 2014. 9 Attendees.

Mattner SW et al. (2014). Three UN Bilateral Meetings between representatives of VSICA, the Victorian strawberry runner industry, Commonwealth Department of the Environment and (1) the UNs Methyl Bromide Technical Options Committee, (2) the European Community Party to the Montreal Protocol, and (3) the Swiss Party to the Montreal Protocol. Meeting of the Parties to the Montreal Protocol, Paris. 15 July 2014. 6 – 15 Attendees.

Mattner SW et al. (2014). Project Co-ordination Group Meeting (meeting). Toolangi Research Farm, Victoria. 19 September 2014. 10 Attendees.

Merriman PR et al. (2014). Meeting between representatives of VSICA, the Victorian strawberry runner industry, and Commonwealth Department of the Environment on (1) outcomes from the study tour of European strawberry nursery industries, and (2) the possible use of MB under a quarantine category in the Australian runner industry. Department of the Environment, Canberra, ACT. 21 October 2014. 7 Attendees.

Mattner SW, Porter IJ, et al. (2014). Update on international regulatory issues with MB, outcomes from the study tour of Europe (oral presentations). Toolangi Research Farm, Victoria. 27 November, 2014. 9 Attendees.

Milinkovic M et al. (2014). Soil-less systems of runner production (field demonstration). Toolangi Research Farm, Victoria. 27 November 2014. 9 Attendees.

Milinkovic M et al. (2015). Soil-less production of strawberry runners (oral presentation). Toolangi Research Station, Toolangi, Victoria. 20 July, 2015. 7 Attendees.

Mattner SW et al. (2015). Project Co-ordination Group Meeting (meeting). Tullamarine Airport, Victoria. 16 September 2015. 10 Attendees.

Mattner SW et al. (2015). Arkema Industry Tour (on-farm meeting and trial inspection). Toolangi, and Yarra Valley, Victoria. 23 October 2015. 8 Attendees.

Mattner SW et al. (2015). BOC Industry Tour (on-farm meeting and trial inspection). Toolangi, Victoria. 26 October 2015. 6 Attendees.

Mattner SW et al. (2015). Update on MB alternatives (oral presentation). Toolangi Research Farm, Toolangi, Victoria. 24 November 2015. 15 Attendees.

Milinkovic M et al. (2015). Soil-less Production of Strawberry Runners (oral presentation). Toolangi Research Farm, Toolangi, Victoria. 24 November 2015. 15 Attendees

Milinkovic M. et al. (2015). Demonstration of Soil-less Production of Strawberry Runners (field demonstration). Toolangi Research Farm, Toolangi, Victoria. 24 November 2015. 15 Attendees.

Mattner SW et al. (2015). Integrated weed control with herbicides and fumigants (oral presentation). Toolangi Research Farm, Toolangi, Victoria. 9 December 2015. 10 Attendees.

Greenhalgh FC et al. (2016). Certified Strawberry Runner Production (field day). Australasian Plant Pathology Society Field Day. Toolangi Research Station, Toolangi, Victoria. 16 February 2016. 33 Attendees.

Mattner SW et al. (2016). Performance of Plug Plants in the Strawberry Fruit Industry (field demonstration). Millgrove, Victoria. 19 February 2016. 8 Attendees.

Mattner SW et al. (2016). MB Alternatives Trials Farm Walk (field day). Toolangi, Victoria. 4 March 2016. 16 Attendees.

Milinkovic M, Barel M., et al. (2016). Grower meeting on steam disinfestation of soil and substrate (oral presentation and demonstration). Toolangi, Victoria. 12 July, 2016. 9 Attendees.

Mattner SW et al. (2016). Department of the Environment / Runner Grower Field Inspections of MB Alternatives Trials (field day). Toolangi & Yarra Valley, Victoria. 11 March 2016. 11 Attendees.

Mattner SW et al. (2016). Three UN Bilateral Meetings between representatives of VSICA, the Victorian strawberry runner industry, Commonwealth Department of the Environment and (1) the UNs Methyl Bromide Technical Options Committee, (2) the European Community Party to the Montreal Protocol, and (3) the Swiss Party to the Montreal Protocol. Meeting of the Parties to the Montreal Protocol, Vienna. 18-20 July 2016. 6 – 8 Attendees.

Mattner et al. (2016). Status of critical-use exemptions and substitutes for MB (oral presentation). Toolangi, Victoria. 29 November, 2016. 16 Attendees.

Milinkovic et al. (2016). Field demonstration of soil-less techniques for strawberry runner production (field walk). Toolangi, Victoria. 29 November, 2016. 16 Attendees.

Mattner SW et al. (2016). Integrated use of substitute fumigants and herbicides for strawberry runner production at Toolangi (oral presentation). TCSRGC AGM, Toolangi, Victoria. 15 December, 2016. 13 Attendees.

Brodie GI, Mattner SW et al. (2016). In-field demonstration of soil disinfestation with a prototype microwave system. Toolangi, Victoria. 21 December, 2016. 15 Attendees.

Mattner SW et al. (2016). Draslovka meeting on EDN registration in Australia. Melbourne, Victoria. 28 December, 2016. 6 Attendees.

Mattner SW et al. (2016) TriCal Industry Tour (on-farm meetings). Toolangi and Yarra Valley, Victoria. 13 March, 2017. 7 Attendees.

Mattner SW et al. (2016) Arkema Industry Tour (on-farm meetings and trial inspections). Toolangi and Yarra Valley, Victoria. 28-29 March, 2017. 12 Attendees.

5.2 Conference Presentations / Papers:

Mattner S.W., 2013. Prospective uses of seed meals for soil disinfestation in horticulture. Asian Pacific Seed Association Congress. Kobe, Japan, 20 November 2013. Keynote Address.

Mattner SW, Milinkovic M., et al., 2016. Addressing critical challenges in the phase-out of methyl bromide in the Australian strawberry industry. Abstract for the International Strawberry Symposium, Quebec, Canada (accepted).

Mattner S.W., Milinkovic M., et al., 2014. Critical challenges for the phase-out of methyl bromide in the Australian strawberry industry: Economics of soil-less production of transplants. Seventh International Symposium on Chemical and Non-Chemical Soil and Substrate Disinfestation. Torino, Italy, July 13-17.

Mattner S.W., Milinkovic M., et al., 2015. Efficacy and plant-back of dimethyl disulphide in the Australian strawberry industry. In Proceedings of the International Methyl Bromide Alternative Outreach Conference, San Diego, November 2015.

Mattner S.W., Milinkovic M., et al., 2015. Evaluation of soil-less systems for strawberry transplant production. International Convention & Exhibition on Soil-less Culture: Hydroponics & Aeroponics. Gold Coast, 5-8 July 2015. Opening Address.

Mattner S.W., Milinkovic M., et al., 2016. Performance of plug plants and fumigants for strawberry runner production in Australia. In Proceedings of the International Methyl Bromide Alternative Outreach Conference, Orlando, November 2016.

Mattner S.W., Thalavaisundaram T., et al., 2015. Virtually impermeable film improves the efficacy of EDN Sterigas® in the Australian strawberry nursery industry. Proceedings of the International Methyl Bromide Alternative Outreach Conference, San Diego, November 2015.

Milinkovic M., Mattner S.W, et al., 2016. Development and performance of soil-less systems for strawberry transplant production in Australia. Abstract for the International Strawberry Symposium, Quebec, Canada (accepted).

Mattner S.W., Porter I.J., et al. 2014. Critical challenges for control of soilborne pathogens in the strawberry industry. In Proceedings of the 8th Australasian Soilborne Diseases Symposium, 10-13 November, Hobart.

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6. Outcomes / Results

6.1 Development of Integrated Soil Disinfestation Systems:

6.1.1 Small-Scale Trials

Overall, no combinations were identified that controlled weeds, pathogens, and produced runner yields to the same level as MB/Pic (500 kg/ha). Several combinations of substitute fumigants and herbicides, however, showed promise for further evaluation.

6.1.1.1 Weed control

Weeds emerging in trials varied from site to site, but the most dominant included: *Acacia* spp. *Amaranthus retroflexus*, *Chenopodium album*, *Digitaria sanguinalis*, *Dysphania ambrosiodes*, *Echinochloa crus-galli*, *Lolium* spp., *Lotus corniculatus*, *Persicaria maculosa*, *Poa annua*, *Raphanus raphanistrum*, *Senecio vulgaris*, *Solanum nigrum*, *Sonchus oleraceus*, *Spergula arvensis*, *Stellaria media*, and *Trifolium* spp.

All substitute fumigants tested significantly and consistently suppressed weed emergence compared with the untreated control, except Pic (e.g. Figure 1). The methyl isothiocyanate generators MS and Daz, or co-application of these products with other substitute fumigants, generally controlled weeds to equivalent levels as MB/Pic (500 kg/ha) (e.g. Figures 1 & 2). However, MS and Daz also reduced runner yields due to crop phytotoxicity (see 'Yield' below). Other substitute fumigants, applied on their own using standard techniques, did not control weeds to the same level as MB/Pic.

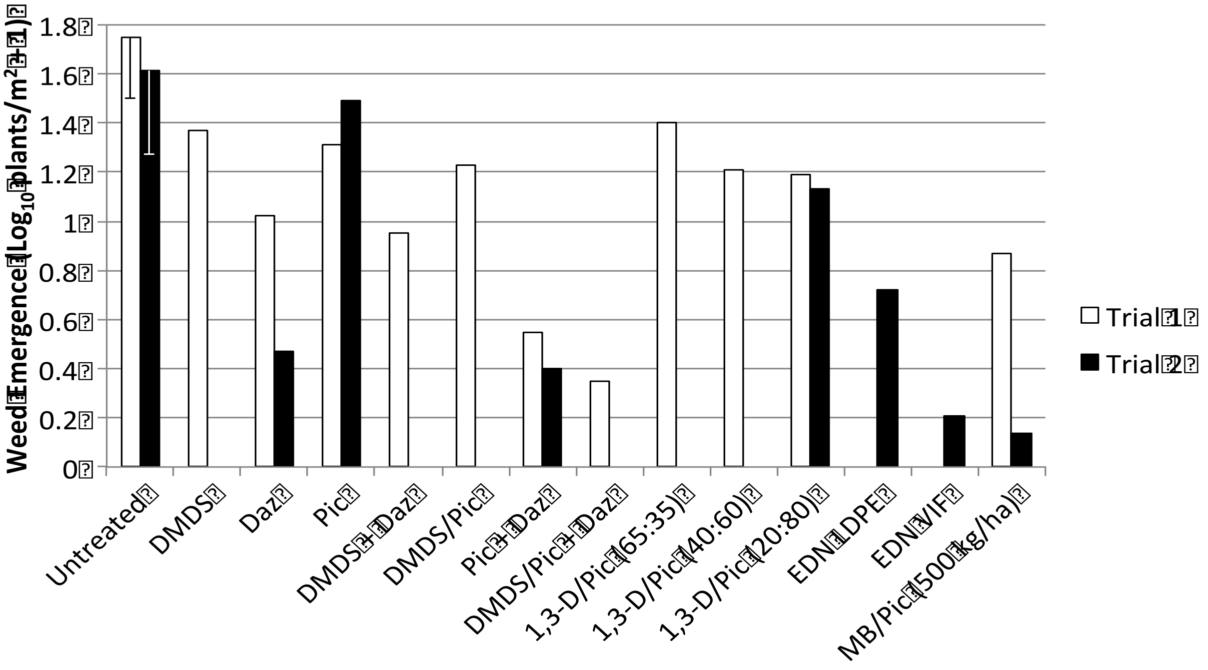

Figure 1. *Weed emergence in soils treated with different fumigants in two field trials in the strawberry runner industry at Toolangi, Victoria in 2014/15. Error bars represent least significant differences for each trial, where p = 0.05.*

All pre-emergent herbicides tested significantly suppressed weed emergence in non-fumigated soil, except α-pinene and chlorthal-dimethyl (e.g. Figure 2). The pre-emergent herbicides napropamide, isoxaben, oxyfluorfen, and terbacil significantly reduced weeds in soils treated with substitute fumigants, to levels equivalent to that in MB/Pic-treated soil. Oxyfluorfen and terbacil, however, killed or suppressed the growth of strawberry plants (see 'Yield' below).

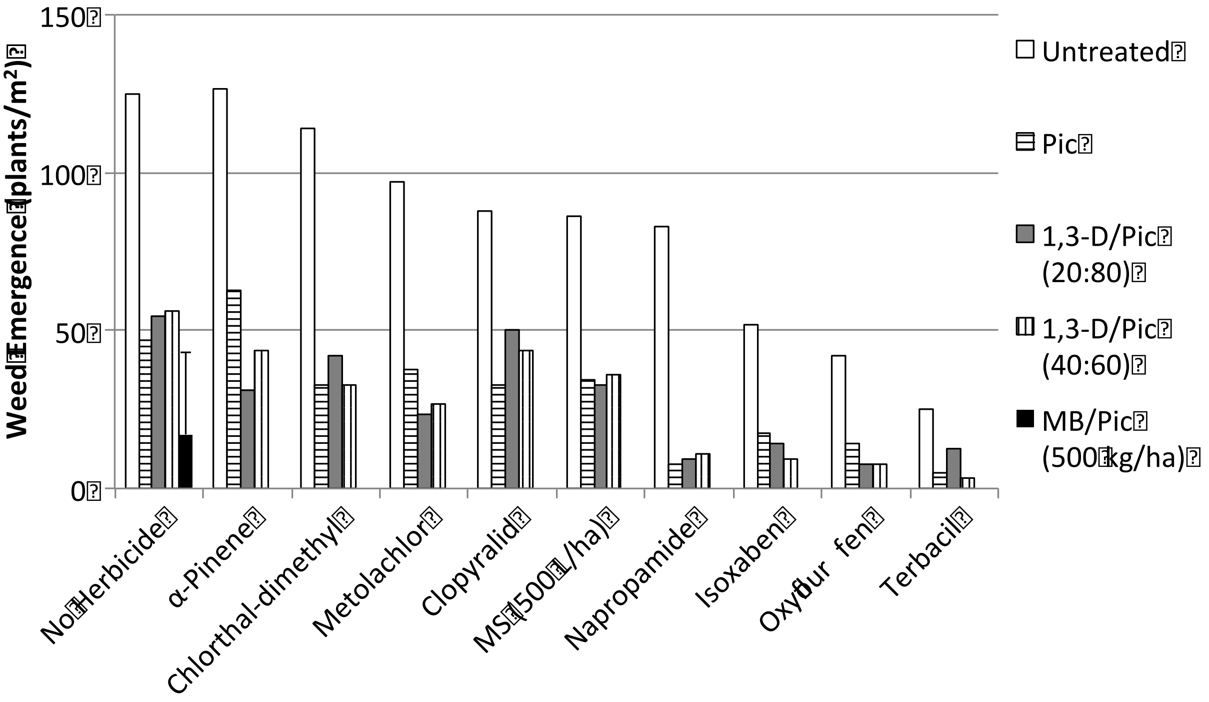

Figure 2. *Weed emergence in soil treated with different combinations of fumigants and pre-emergent herbicides in a field trial in the strawberry runner industry at Toolangi, Victoria in 2013/14. The error bar represents the least significant difference, where p = 0.05.*

The post-emergent herbicide phenmedipham significantly controlled weeds compared with the untreated control, but fluazifop-p did not consistently do so (e.g. Figure 3). Spray programs using the pre-emergent herbicide isoxaben and the post-emergent herbicides phenmedipham and fluazifop-p significantly controlled weeds in untreated soils, and in soils treated with substitute fumigants (e.g. Pic and 1,3-D/Pic (20:80)), to equivalent levels as MB/Pic (500 kg/ha) (e.g. Figures 3 & 4).

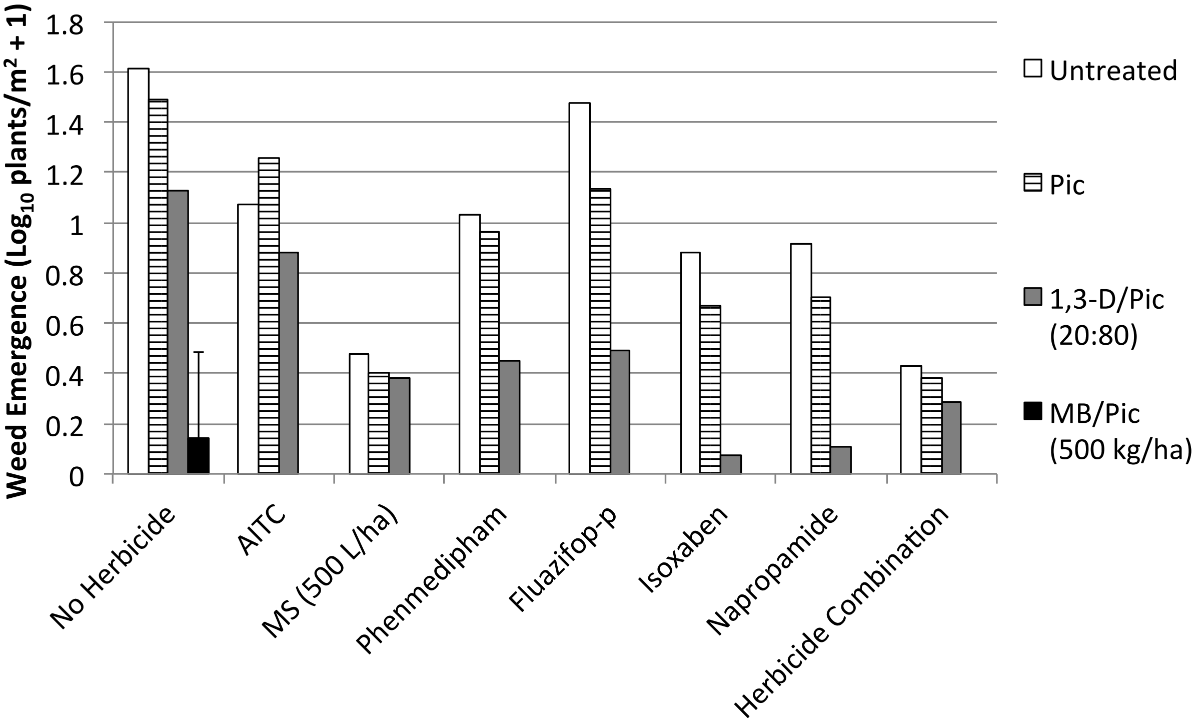

Figure 3. *Weed populations in soil treated with different combinations of fumigants and pre- and post-emergent herbicides in a trial in the strawberry runner industry at Toolangi, Victoria in 2014/15. The herbicide combination consisted of isoxaben + phenmedipham + fluazifop-p. The error bar represents the least significant difference, where p = 0.05.*

The use of virtually impermeable barrier films, compared with LDPE, significantly increased weed control by the substitute fumigant EDN (e.g. Figure 1), to levels equivalent to MB/Pic (500 kg/ha). The use of VIFs did not increase weed control by 1,3-D/Pic (20:80) (data not shown). Deeper injection (to a soil depth of 25 cm compared with 15 cm) of the substitute fumigant EDN significantly increased weed control, but deeper application of 1,3-D/Pic (20:80) significantly decreased it (e.g. Figure 4).

Decreasing the application rate of MB/Pic from the standard of 500 kg/ha to 400 kg/ha significantly and consistently reduced weed control (e.g. Figure 4).

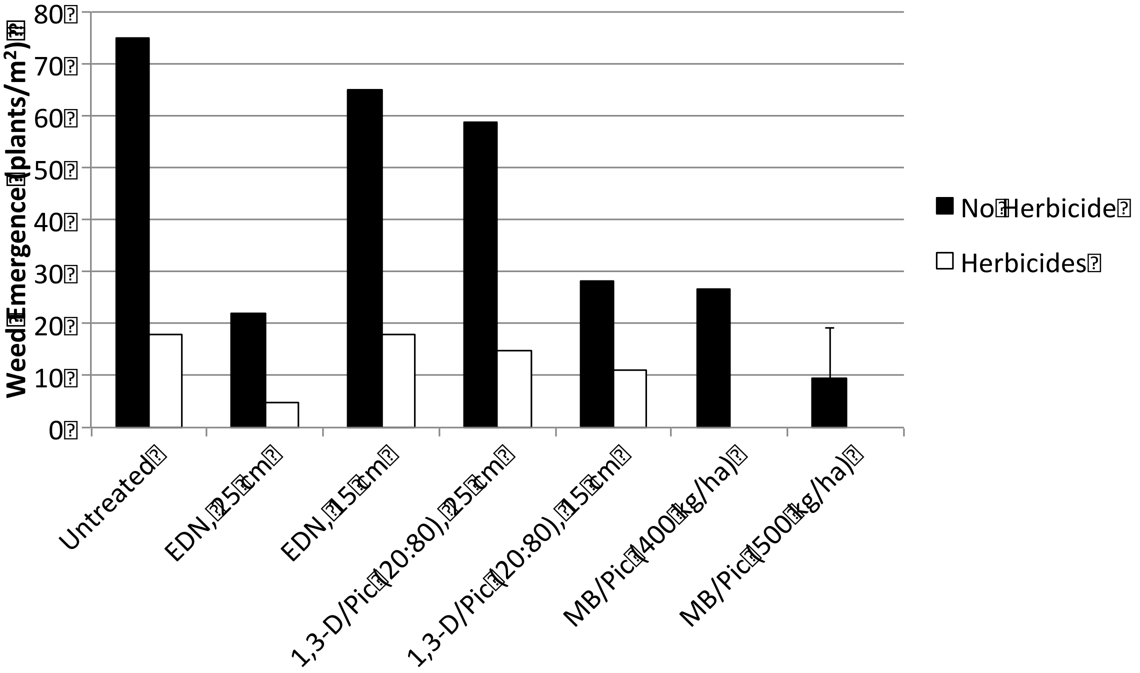

Figure 4. *Weed emergence in soil treated with combinations of fumigants, applied at different soil depths (25 cm and 15 cm), and pre- and post-emergent herbicides in a trial in the strawberry runner industry at Toolangi, Victoria in 2015/16. Herbicide treatment consisted of isoxaben + phenmedipham + fluazifop-p. The error bar represents the least significant difference, where p = 0.05.*

6.1.1.2 Pathogen control

MB/Pic (500 kg/ha) was the only treatment that consistently eradicated buried inoculum of all pathogens in soils in all trials. However, some combinations of substitute fumigants (e.g. 1,3-D/Pic (20:80) and DMDS or DMDS/Pic + MS or Daz) showed the potential to control buried pathogens to the same level as MB/Pic (500 kg/ha) in individual trials (e.g. Figure 5).

Natural populations of soil-borne pathogens occurred at low levels in the trials. DNA concentrations of *Pythium* spp. clade F were the highest of those tested at the sites (99.2% of total pathogen DNA). Clade F contains the species *P. debaryanum*, *P. irregulare* and *P. sylvaticum*, which are important pathogens of strawberry plants. Concentrations of other strawberry pathogens at the trial sites were extremely low: *Pythium* spp. clade I (0.7% of total pathogen DNA), *Meloidogyne hapla* (0.004% of total pathogen DNA) and *Pratylenchus penetrans* and *Verticillium dahliae* (< 0.001% of total pathogen DNA). DNA concentrations of *Macrophomina phaseolina* were not detected in soil at any of the trial sites.

At planting, most substitute fumigants significantly reduced total DNA concentrations of pathogens in soil compared with the untreated control. However, no substitute fumigant reduced total pathogen concentrations to the same level as MB/Pic (500 kg/ha), particularly low in the soil profile (e.g. Table 3). There was evidence that pathogens surviving low in the profile re-colonised the upper profile in soils treated with substitute fumigants. For example, by harvest, pathogen concentrations in soil treated with substitute fumigants were equivalent to those in untreated soil, and significantly higher than those in the MB/Pic (500 kg/ha) treatment (e.g. Table 3).

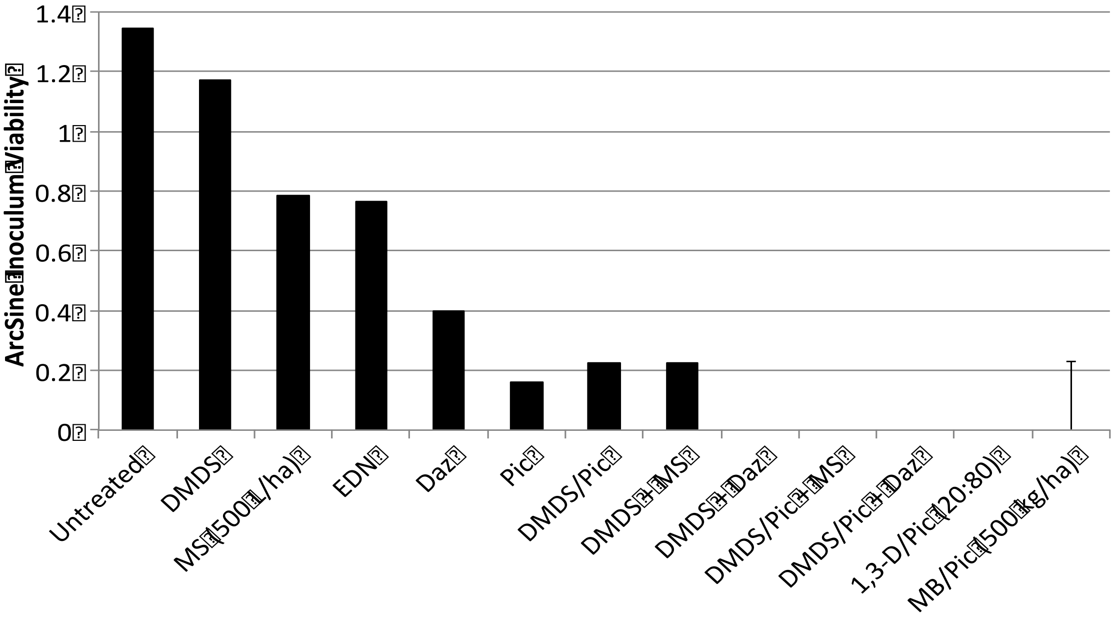

Figure 5. *Viability of buried inoculum (infected barley seed) of Fusarium oxysporum in soils treated with different fumigants in trials in the strawberry runner industry at Toolangi, Victoria in 2015/16. The error bar represents the least significant difference, where p = 0.05.*

Table 3. *Total DNA concentrations of pathogens (Pythium clades I & F, Meloidogyne hapla, Pratylenchus penetrans, and Verticillium dahliae) in soil at different depths following treatment with fumigants in a field trial in the strawberry runner industry at Toolangi, Victoria in 2014/15. Values followed by different letters in each sampling period (planting or harvest) are significantly different, where p ≤ 0.05.*

Fumigant Treatment	**Total Pathogen Concentration (Log$_{10}$ pg DNA / g soil)**			
	Planting		**Harvest**	
	0 – 10 cm	**40 – 50 cm**	**0 – 10 cm**	**40 – 50 cm**
Untreated	2.36 g	2.09 fg	3.01 b	2.84 b
EDN, LDPE	1.69 cde	2.17 fg	2.66 b	2.54 b
EDN, VIF	1.35 bc	1.97 efg	2.78 b	2.80 b
Pic	1.55 cd	1.82 def	2.80 b	2.49 b
1,3-D/Pic (20:80)	0.83 a	1.48 bcd	2.89 b	2.72 b
MB/Pic	0.77 a	1.14 ab	1.32 a	1.29 a
Least Significant Difference (p = 0.05)	**0.40**		**0.56**	

The use of VIF barriers, compared with LDPE, did not significantly increase pathogen control by the substitute fumigants EDN and 1,3-D/Pic (20:80) (e.g. Table 3). Deeper injection (to a soil depth of 25 cm compared with 15 cm) of the substitute fumigants EDN and 1,3-D/Pic (20:80) did not significantly increase pathogen control at soil depths of 40-50 cm (e.g. Figure 6). The use of specific fungicides active against *Pythium* spp. (fosetyl-Al and thiophanate methyl / etridiazole) did not increase pathogen control in soils treated with substitute fumigants (data not shown).

Decreasing the application rate of MB/Pic from the standard of 500 kg/ha to 400 kg/ha significantly reduced pathogen control (e.g. Figure 6).

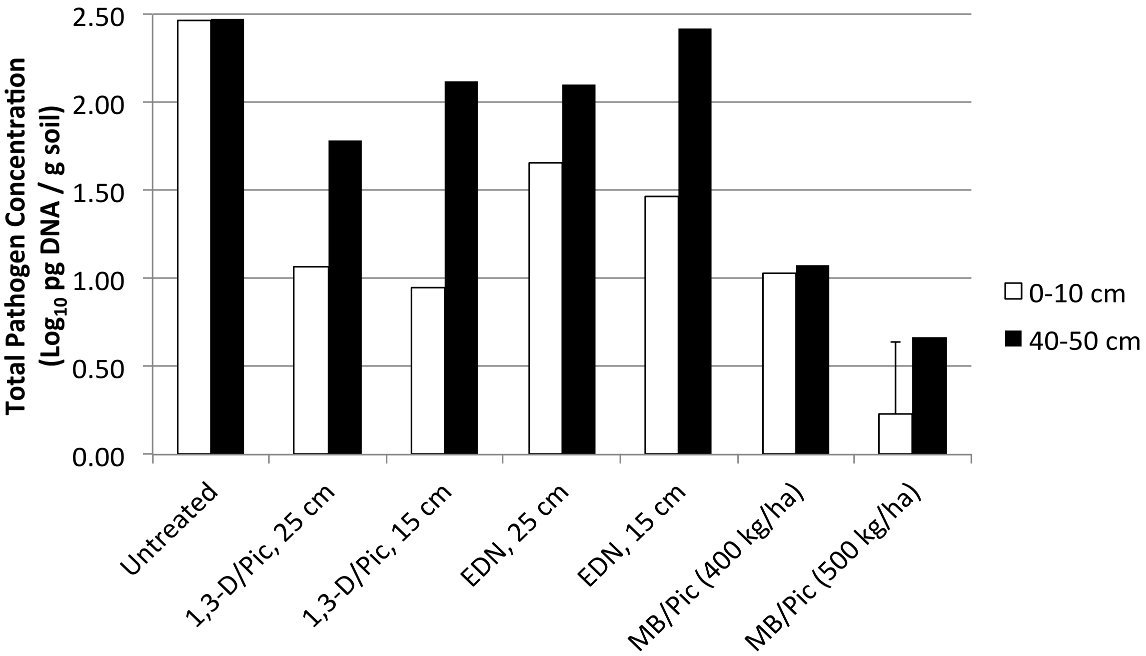

Figure 6. *Total DNA concentrations of pathogens (Pythium clades I & F, Meloidogyne hapla, Pratylenchus penetrans, and Verticillium dahliae) in soil at different soil depths (0-10 cm and 40-50 cm) following treatment with fumigants injected to different soil depths (25 cm and 15 cm) in a field trial in the strawberry runner industry at Toolangi, Victoria in 2015/16. The error bar represents the least significant difference where p = 0.05.*

6.1.1.3 Runner yields

Soil disinfestation with several substitute fumigants showed potential for producing runner yields equivalent to MB/Pic, including DMDS/Pic co-applied with herbicides, 1,3-D/Pic (20:80) co-applied with herbicides, and EDN sealed under VIF (e.g. Figures 7, 8, 9 & 10). Several substitute fumigants caused crop phytotoxicity and significantly reduced runner yields, particularly the methyl isothiocyanate generators Daz and MS (e.g. Figures 7 & 8). Formulations of 1,3-D/Pic containing high concentrations of 1,3-D (i.e. 1,3-D/Pic (65:35) and 1,3-D/Pic (40:60)) also caused phytotoxicity in runner crops, and produced significantly lower runner yields than formulations containing low concentrations of 1,3-D (i.e. 1,3-D/Pic (20:80)) (e.g. Figure 7).

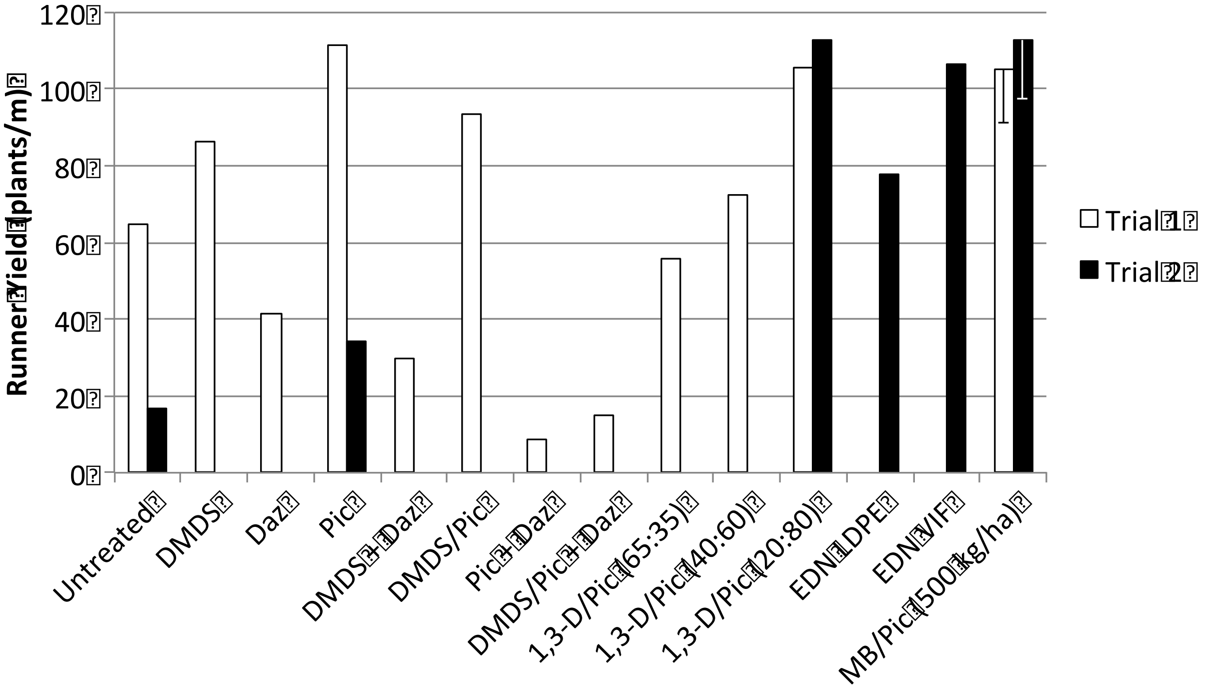

Figure 7. *Runner yields in soils treated with different fumigants in two field trials in the strawberry runner industry at Toolangi, Victoria in 2014/15. Trial 1 was with the cultivar Gaviota, and Trial 2 was with the cultivar San Andreas. Error bars represent least significant differences for each trial, where p = 0.05.*

The pre-emergent herbicides oxyfluorfen and terbacil killed or severely stunted the growth of strawberry runners (e.g. Figure 8). Application of isoxaben at planting significantly increased runner yields in untreated soil, and in soil treated with substitute fumigants (e.g. Figures 8 & 9). Runner yields in plots treated with isoxaben and substitute fumigants were equivalent to those in MB/Pic-treated soil.

The post-emergent herbicides phenmedipham and fluazifop-p did not cause phytotoxicity or losses in yield of strawberry runners. In untreated soils, post-emergent application of phenmedipham and fluazifop-p significantly increased runner yields. Plots treated with 1,3-D/Pic (20:80) followed by spray programs of the pre-emergent herbicide isoxaben and the post-emergent herbicides phenmedipham and fluazifop-p produced equivalent runner yields to MB/Pic (500 kg/ha).

The use of VIF barriers with the substitute fumigant EDN significantly increased runner yields, compared with the use of LDPE (e.g. Figure 7). Deeper injection (25 cm depth compared with 15 cm) of EDN under VIF also significantly increased runner yields (e.g. Figure 10). Depth of application of the substitute fumigant 1,3-D/Pic (20:80) did not affect runner yields (e.g. Figure 10).

Decreasing the application rate of MB/Pic from the standard of 500 kg/ha to 400 kg/ha significantly reduced runner yields (e.g. Figure 10).

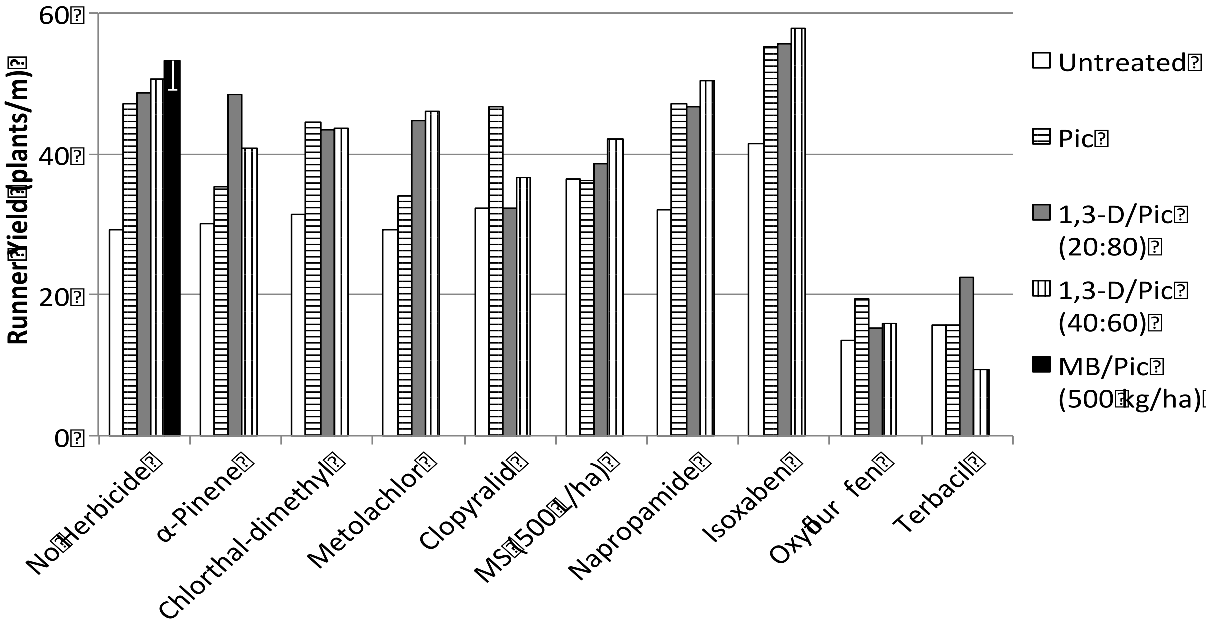

Figure 8. *Runner yields (cv. Monterey) in soil treated with different combinations of fumigants and pre-emergent herbicides in a field trial in the strawberry runner industry at Toolangi, Victoria in 2013/14. The error bar represents the least significant difference, where p = 0.05.*

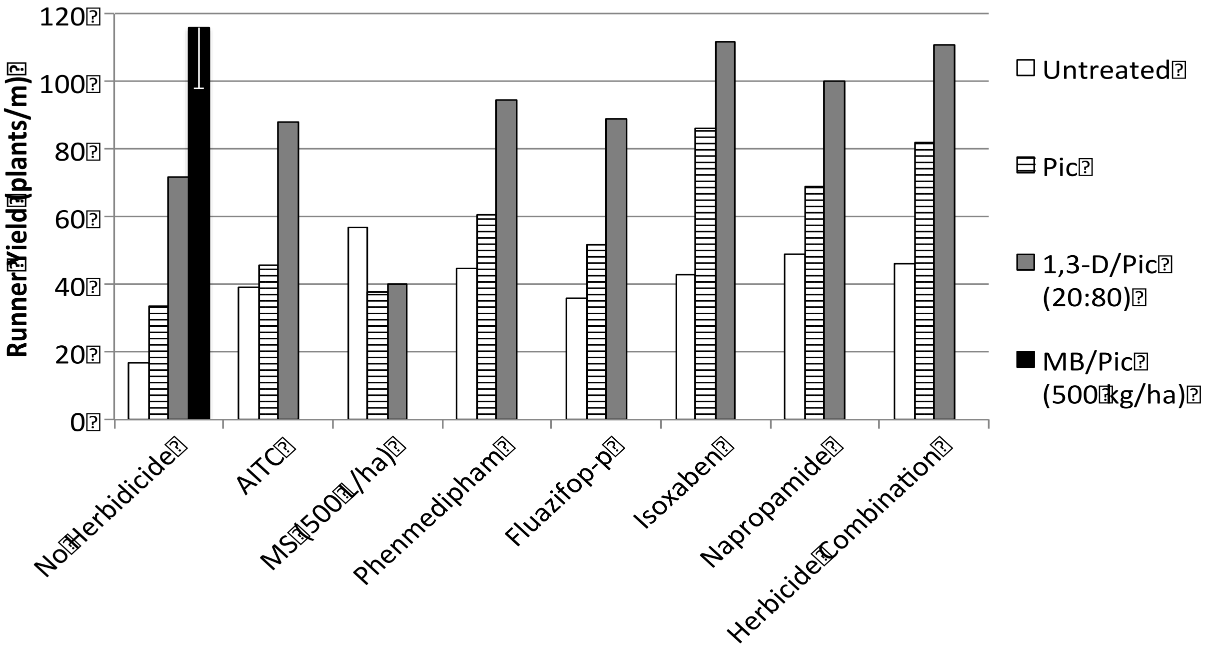

Figure 9. *Runner yields (cv. San Andreas) in soil treated with different combinations of fumigants and pre- and post-emergent herbicides in a trial in the strawberry runner industry at Toolangi, Victoria in 2014/15. The herbicide combination consisted of isoxaben + phenmedipham + fluazifop-p. The error bar represents the least significant difference, where p = 0.05.*

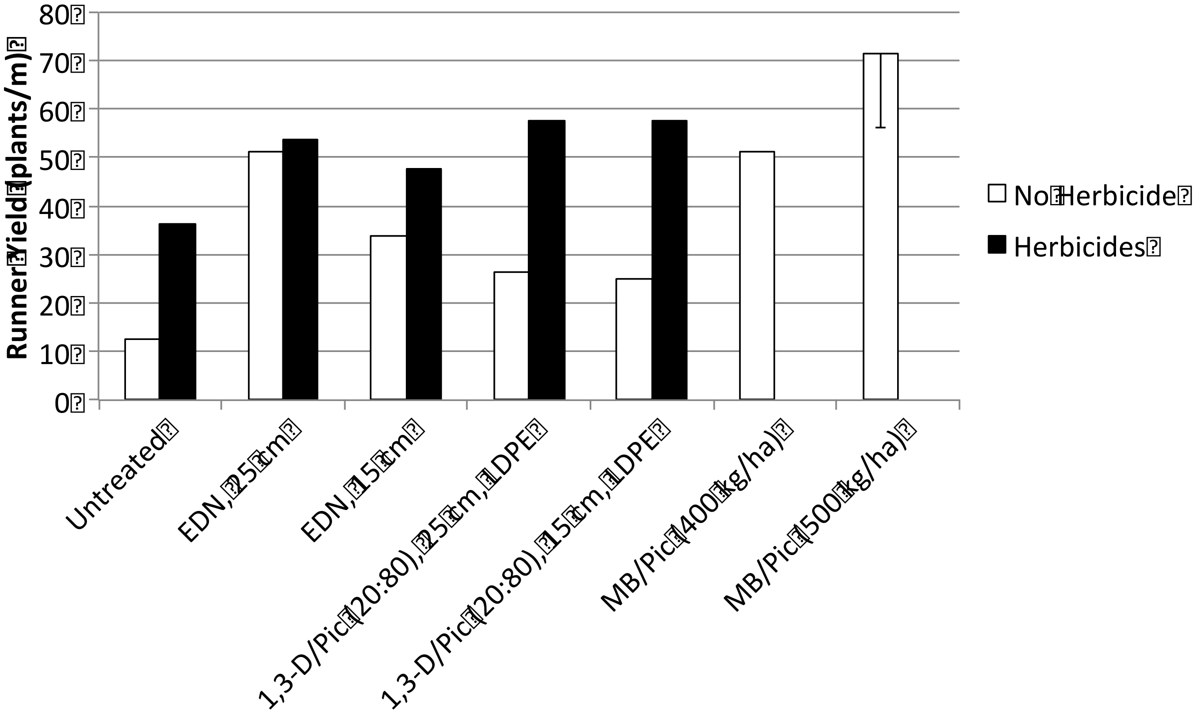

Figure 10. *Runner yields (cv. Albion) in soil treated with combinations of fumigants, applied at different soil depths (25 cm and 15 cm), and pre- and post-emergent herbicides in a trial in the strawberry runner industry at Toolangi, Victoria in 2015/16. Herbicide treatment consisted of isoxaben + phenmedipham + fluazifop-p. The error bar represents the least significant difference, where p = 0.05.*

6.1.1.4 Plant-back:

Concentrations of the active generated by Daz (methyl isothiocyanate) persisted in soil for 126 days after application (Figure 11). Concentrations of 1,3-D persisted in soil for 84 days after treatment with 1,3-D/Pic (65:35) or (40:60), but only 42 days after treatment with 1,3-D/Pic (Figure 12). In comparison, concentrations of MB persisted in soil for 14 days after treatment with MB/Pic 500 kg/ha (Figure 11 & 12).

Models predicted that the plant-back times for the substitute fumigants Pic and 1,3-D/Pic (20:80) were similar to MB/Pic 500 kg/ha (Table 4). Formulations of 1,3-D/Pic containing high concentrations of 1,3-D (i.e. 65:35 and 40:60) required longer plant back times than formulations containing low concentrations of 1,3-D (i.e. 20:80).

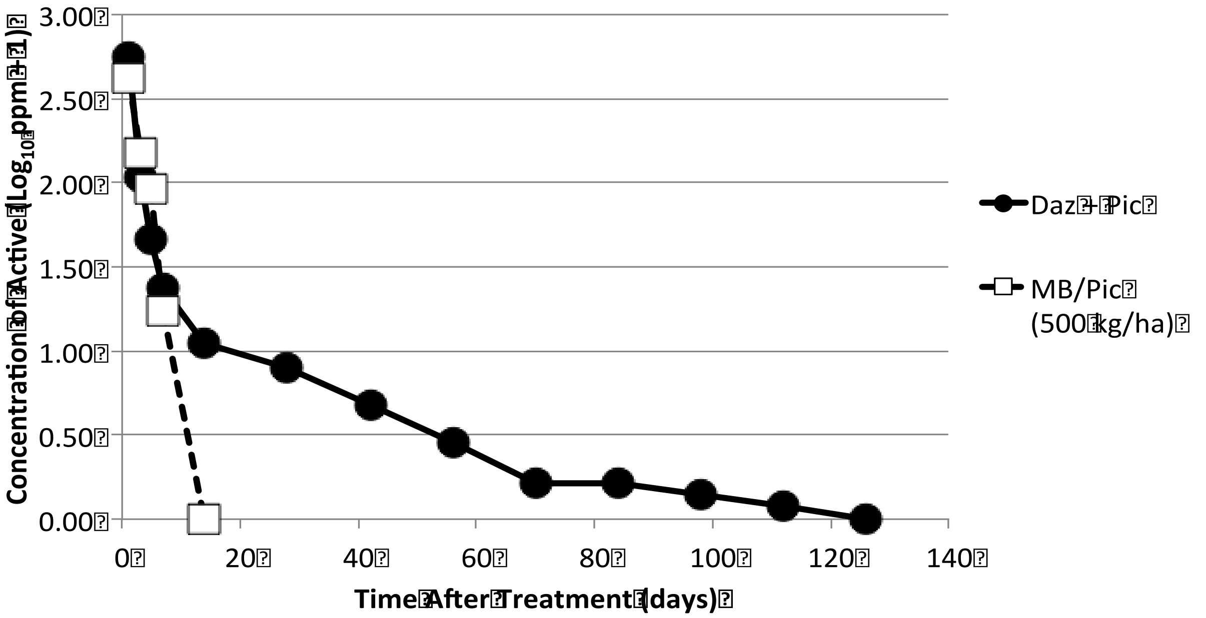

Figure 11. *Concentrations of methyl isothiocyanate (residual active in Daz + Pic) and MB (active in MB/Pic) following treatment in a field trial in the strawberry runner industry at Toolangi, Victoria in 2014/15.*

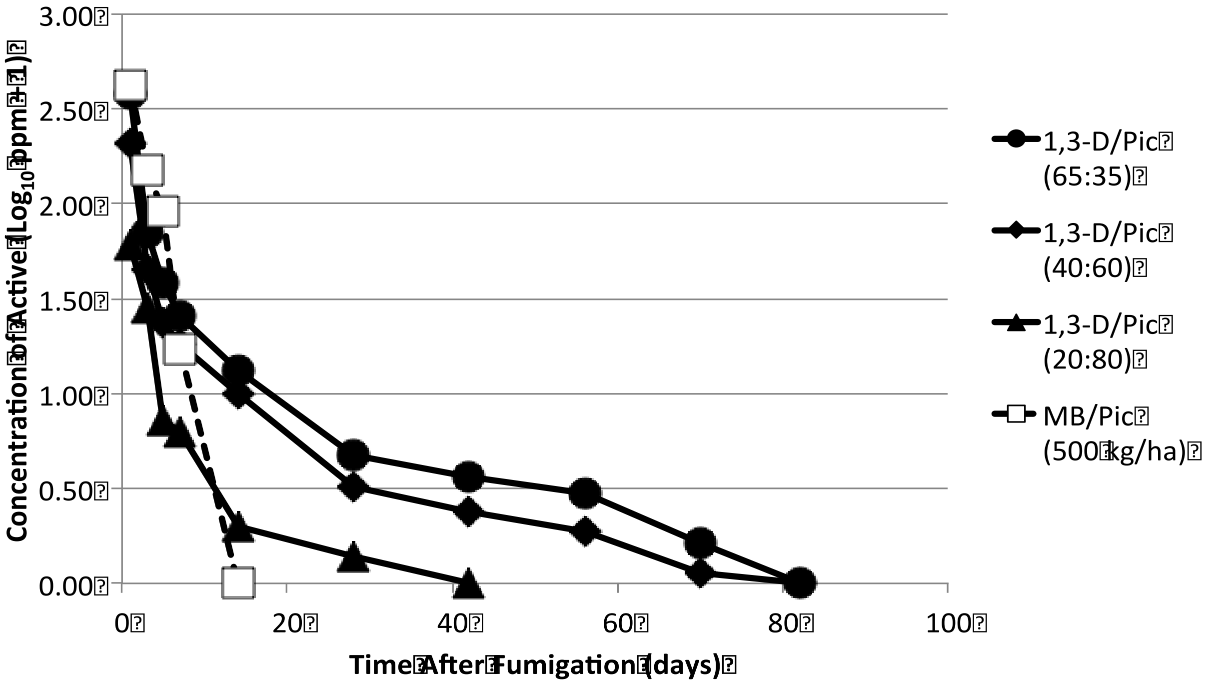

Figure 13. *Concentrations of 1,3-D (residual active in 1,3-D/Pic formulations) and MB (active in MB/Pic) following treatment in a field trial in the strawberry runner industry at Toolangi, Victoria in 2014/15.*

Table 4. *Predicted optimum plant-back times for different fumigants in a field trial in the strawberry runner industry at Toolangi, Victoria in 2014/15, using a modelling approach (Mattner et al., 2003).*

Fumigant Treatment	Optimum Plant-Back Time (P_{opt}) (days)	Log_{10} Maximum Relative Yield (Ym)	Variance Accounted For (%)
DMDS	21.7	2.17 ± 0.02*	99.8
DMDS/Pic	21.7	2.27 ± 0.07	99.7
Pic	16.1	2.28 ± 0.02	99.9
Daz + Pic	86.1	2.35 ± 0.17	99.5
1,3-D/Pic (65:35)	43.4	2.23 ± 0.06	98.6
1,3-D/Pic (40:60)	37.1	2.24 ± 0.04	99.3
1,3-D/Pic (20:80)	16.7	2.29 ± 0.02	99.9
MB/Pic (500 kg/ha)	17.5	2.31 ± 0.07	99.7

* 95% confidence interval

6.1.2 Commercial Trials

6.1.2.1 Commercial trials with Pic

Pathogen concentrations in soil at planting and weed emergence were significantly higher in two runner fields treated with Pic, compared with MB/Pic (500 kg/ha). In one trial, runner yields in a field treated with Pic were equivalent to those in a field treated with MB/Pic (500 kg/ha). In the other trial, runner yields were significantly lower in soils treated with Pic than in those treated with MB/Pic (500 kg/ha).

Subsequent fruit yields at Millgrove, Victoria from runners produced in Pic-treated soils in the nursery were significantly lower than those from runners produced in MB/Pic-treated soils in the nursery (9% lower). This was equivalent to a 10% loss in revenue from fruit, or $0.45 less per plant. At the final fruit harvest, the incidence of Pythium rot was significantly higher in plants grown from runners produced in Pic-treated soil (50% of structural roots with lesions) than in those from runners produced in MB/Pic-treated soil (33% of structural roots with lesions). The incidence of recovery of *Pythium* spp. from the structural roots of strawberry plants grown from runners produced in soil treated with Pic was significantly higher (38%) than those grown from runners produced in MB/Pic-treated soil (12%).

Table 5. *Summary of results from five commercial trials comparing the efficacy of substitute fumigants to MB/Pic in the strawberry runner industry at Toolangi, Victoria. Means are followed by 95% confidence intervals.*

Cultivar	Fumigant Treatment	Weed Emergence (plants/m²)	Total Pathogen Concentration (pg DNA /g soil)	Runner Yields (plants/m)
Trial 1: Albion	Pic	53.7 ± 12.1	12.53 ± 5.43	97.9 ± 14.2
	MB/Pic (500 kg/ha)	4.8 ± 3.9	2.06 ± 2.58	102.7 ± 12.2
Trial 2: Palomar	Pic	42.6 ± 6.0	78.24 ± 21.33	97.9 ±7.1
	MB/Pic (500 kg/ha)	7.4 ± 3.2	1.06 ± 0.87	118.0 ± 9.0
Trial 3: Albion	1,3-D/Pic (20:80) + isoxaben	4.1 ± 0.7	8.71 ± 5.57	111.2 ± 4.2
	MB/Pic (500 kg/ha)	1.5 ± 0.3	0.60 ± 0.39	130.0 ± 4.5
Trial 4: Monterey	1,3-D/Pic (20:80) + isoxaben	3.1 ± 0.6	7.90 ± 2.74	141.8 ± 7.9
	MB/Pic (500 kg/ha)	2.4 ± 0.3	2.28 ± 0.34	144.7 ± 6.2
Trial 5: Fortuna	1,3-D/Pic (20:80) + isoxaben	2.5 ± 0.2	19.75 ± 9.67	111.9 ± 11.6
	MB/Pic (500 kg/ha)	2.1 ± 0.4	0.34 ± 0.29	117.5 ± 6.1

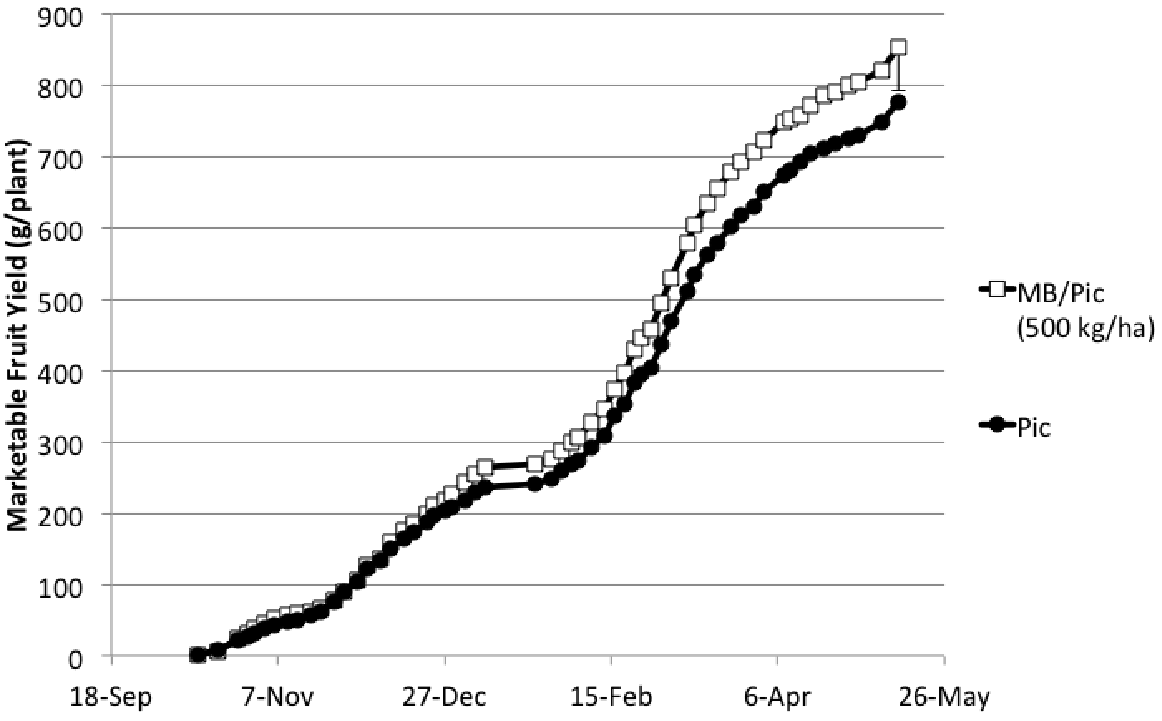

Figure 14. *Cumulative fruit yields (cv. Albion) in a field trial at Millgrove, Victoria from runners sourced from different fumigant treatments in the strawberry nursery industry. The error bar represents the least significant difference, where p = 0.05, at the final harvest.*

6.1.2.2 Commercial trials with 1,3-D/Pic (20:80) + isoxaben:

At planting, pathogen concentrations in soil were significantly higher in three fields treated with 1,3-D/Pic (20:80) + isoxaben, compared with MB/Pic (500 kg/ha) (Table 5). In two of the three trials, weed control and runners yields were equivalent in fields treated with 1,3-D/Pic (20:80) + isoxaben, or MB/Pic. In the other trial, weed control and runner yields were significantly lower in fields treated with 1,3-D/Pic (20:80) + isoxaben than in those treated with MB/Pic (500 kg/ha).

Subsequent fruit yields at Wanneroo, Western Australia from runners produced in 1,3-D/Pic (20:80) + isoxaben-treated soils in the nursery were significantly lower than those from runners produced in MB/Pic-treated soils in the nursery (15% lower fruit yields), particularly late in the season when wholesale prices for fruit were high (Figure 15). This was equivalent to a loss in revenue from fruit of 16%, or $1.17 per plant. There was no significant difference in the incidence of Fusarium wilt or *Fusarium oxysporum* recovered from the roots of strawberry plants grown from runners produced in 1,3-D/Pic (20:80) + isoxaben or MB/Pic treatments (data not shown).

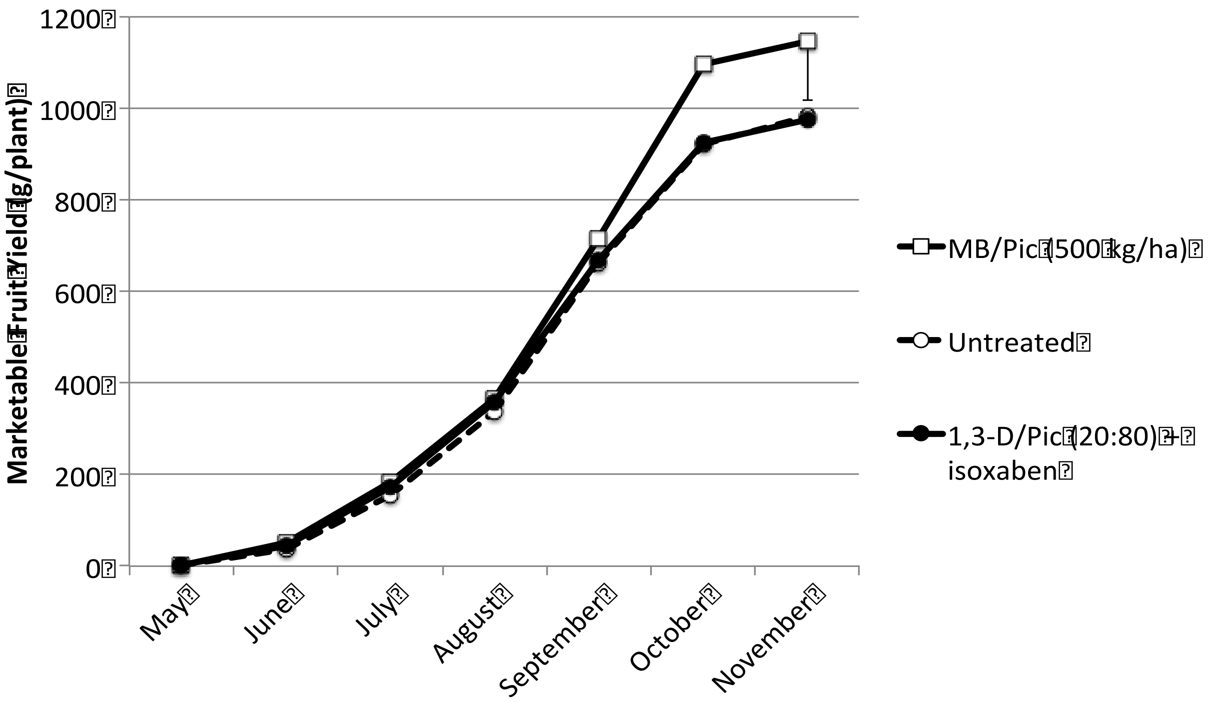

Figure 15. *Cumulative fruit yields (cv. Fortuna) in a field trial at Wanneroo, Western Australia from runners sourced from different fumigant treatments in the strawberry nursery industry. The error bar represents the least significant difference, where p = 0.05, at the final harvest.*

6.2 Soil-less Systems for Production of Strawberry Runners:

6.2.1 Feasibility Analyses

A literature review on soil-less systems for strawberry runner production was published in the scientific literature (Mattner et al., 2016; see 'Scientific Refereed Publications'), in a report submitted to industry, the Department of the Environment and United Nations, and presented as an opening address at the International Convention on Soil-less Culture (see 'Outputs'). The key recommendation from the review was that further research is needed to improve the economics and consistency of fruit yields from transplants produced in soil-less systems. In particular, the combination of micro-propagated mother plants, tip production in hydroponics, and conditioned plug transplants shows the greatest potential.

Results from a partial budget analysis were also published in the scientific literature (Mattner et al., 2014; see 'Scientific Refereed Publications') and in critical-use nominations submitted to the United Nations. Analysis showed that production of Mother (third generation) and Certified (fourth generation) runners in substrate bins would result in net revenue losses of nearly $800,000/ha, or 83% (Table 6). Prices of runners would need to increase from $0.34 in MB/Pic-treated soils, to $2.00 per transplant in substrate bins just to break even (Table 6).

Table 6. *Summary of the economic impacts of soil-less systems (substrate bins) for production of the Certified generation of strawberry runners at Toolangi, Victoria.*

Certified Transplant Production	Commercial Production in Soil-less Substrate (2011/12)	Commercial Production in MB/Pic-Treated Soil (2011/12)
A. Production per hectare (transplants/ha)	475,000.00	576,364.64
B. Production loss compared with MB/Pic (%)	17.59	0.00
C. Price per unit (A$/transplant)	0.34	0.34
D. Gross revenue per hectare ($A) [A × C]	161,500.00	195,963.63
E. Operating costs per hectare (A$)	783,760.33	153.782.59
F. Capital costs per hectare (A$)	166,814.38	27,212.78
G. Total costs per hectare (A$) [E + F]	950,574.71	180,955.37
H. Net revenue per hectare (A$) [D – G]	-789,074	15,008.26
I. Operating profit margin (%) [(H÷G) × 100]	-83.0	8.3
J. Required price per unit to break even (A$/runner) [G÷A]	2.00	0.31

6.2.2 Study Tours

6.2.2.1 Japan

In the Nagasaki Prefecture of Japan, strawberry fruit growers produce their own transplants (70-80%) using soil-less rack systems. In this system, mother plants are grown in soil-less substrates (65% mountain soil: 15% peat moss: 10% coconut coir: 10% composted pine bark) in pots. Daughter plants are pinned into smaller pots containing the soil-less substrate, and these form the planting stock for the subsequent generation. Pathogen-tested stock are also produced using the same method by dedicated nurseries, but only occupy 4% of the market due to their high cost (A$2.40 per plant). Key production and economic differences (Table 7) mean that the Japanese rack system is not a direct substitute for runner production in MB/Pic-treated soil in Australia. However, the Victorian Runner Certification Scheme has adopted a similar substrate system to Japan for production of Nucleus stock (first generation) runners.

Table 7. *A comparison of key production, biosecurity, and economic differences that prevent Japanese rack systems from being an immediate substitute for Mother and Certified stock production in Victoria, Australia.*

Situation in Japan	**Situation in Australia**
Production / Biosecurity Differences	
Strawberry fruit growers are allowed to produce their own transplants using substrate systems, which reduces the cost of production.	Plant breeder rights for strawberry cultivars grown in Australia prohibit fruit growers from producing their own transplants.
Dedicated strawberry nurseries produce just 4% of transplants using pathogen-tested Schemes (80,000 plants in total from Nagasaki Prefecture).	Strawberry nurseries produce 100% of transplants using pathogen-tested Schemes (60 million plants from Victoria alone), which maintains high levels of plant health and biosecurity in the national industry. High health status of strawberry runners is essential for high yields and economic feasibility in the fruit industry.
Strawberry yields in the rack system can be less than 10 per mother plant. Lower yields are less critical because individual growers produce small amounts of transplants for their own use.	Strawberry runner yields in MB/Pic-treated soil are 100-200 per mother plant, and up to 150 per mother plant in soil-less systems. High yields are critical to reduce costs and ensure supply for the entire fruit industry (60 million from Victoria alone).
Economic Differences	
The price of pathogen-tested transplants is A$2.44 per plant.	The price of pathogen-tested runners produced in MB/Pic-treated soil is A$0.34 per plant.
Labour costs were reported at A$10/hour.	Labour costs are A$24/hour.
Fruit growers were reported to fetch a minimum of A$10.25/kg of fruit.	Fruit prices are highly variable, but fetch an average of A$6.35/kg at the Melbourne markets (FreshLogic, 2015)

6.2.2.2 Europe

In 2014, a contingent of Victorian runner growers and VSICA members visited strawberry nurseries in Spain (Ekland Group, Viveros Campiñas, and Viveros Mozoncillo) and the Netherlands (NAK, Goosens Flevo Plant, De Kemp BV, Neesen BV, and Van Alphen). Spanish nurseries reported that they import nucleus runners from California, USA, which are produced in soil treated with MB/Pic under a quarantine exemption. The Dutch strawberry nursery industry reported that it produced 1 billion transplants p.a. It was also reported that up to 30% of these transplants are containerised tray plants produced in soil-less media. Ninety percent of the runner tips used to produce tray plants are grown in the field in soil. Therefore, this system does not eliminate the need for soil disinfestation and does not present the Victorian runner industry with a substitute to MB/Pic. The remaining 10% of runner tips used to produce tray plants in the Netherlands were produced in hydroponic systems. This system does eliminate the need for soil disinfestation, but only occupies a small proportion of transplant production by the European industry (3% in total, equivalent to 3 million transplants). Economic, market, and environmental differences mean that European hydroponic / tray plant systems are not an immediate substitute for MB/Pic and runner production in Australia (Table 8).

Table 8*. A comparison of key production, biosecurity, and economic differences that prevent European tray plant systems from being an immediate substitute for Mother and Certified stock production in Victoria, Australia.*

Situation in Europe	**Situation in Australia**
Production Differences	
Tray plants are adopted because they extend the growing season for fruit growers and increase fruit yields (Hennion et al., 1997; Lieten et al., 2004; Lieten, 2013).	Plug plants do not extend the growing season and have not delivered consistently higher yields in current and previous studies (Menzel & Waite, 2006; Menzel & Toldi, 2010).
It was reported that 90% of mother stock used to produce tray plants in Spain were imported from the USA, where they were produced in soils disinfested with MB/Pic under a quarantine exemption.	Mother plants of Foundation stock (second generation) are already produced in soil-less substrate, and not in soil treated with MB/Pic.
Economic Differences	
The Dutch industry alone produces 1 billion transplants p.a. and this creates large economies of scale for tray plant production.	The Victorian runner industry produces 60 million runners.
Labour costs were reported at A$9-12/hour.	Labour costs are A$24/hour.
The cost of tray plants was 2.5-times the cost of bre-rooted runners. Fruit growers can afford this cost increases because tray plants increase the growing season and produce higher fruit yields than bare-rooted runners.	Cost increases for plug plants in Australia are not accepted by fruit growers because they do not currently yield as consistently well as bare-rooted runners (Menzel & Toldi, 2010).

6.2.2.3 South Africa

Nursery growers at Brits, Ceres, and George produced plug plants in similar hydroponic systems to those observed in Europe, but designs (e.g. support structures, gutters, netting, substrate) varied considerably from farm to farm. The price of plug plants was only 1.4 times more than bare-rooted runners produced in fumigated soil, due to the relatively low costs of labour (A$1.50/hour) and infrastructure. None of the technologies used for the production of tips and plug plants in soil-less systems in South Africa, however, are immediately transferable for the economic production of plug plants in Australia (Table 9). However, design aspects from hydroponics systems in Europe and South Africa were used to develop a prototype hydroponic system for evaluation of plug plant production in Victoria (see below).

Table 9. *A comparison of key production, biosecurity, and economic differences that prevent South African plug plant systems from being an immediate substitute for Mother and Certified stock production in Victoria, Australia.*

Situation in Europe	**Situation in Australia**
Production / Biosecurity Differences	
No pathogen-tested Schemes for strawberries. Growers largely maintain their own propagation material and the health status of commercially produced plants are not tested. High health status of strawberry runners or plugs is not necessary for economic feasibility in the fruit industry.	Strawberry nurseries produce 100% of transplants using pathogen-tested Schemes (60 million plants from Victoria alone), which maintains high levels of plant health and biosecurity in the national industry. High health status of strawberry runners is essential for high yields and economic feasibility in the fruit industry.
Strawberry fruit growers can produce their own plug plants to reduce costs.	Plant breeder rights for strawberry cultivars grown in Australia prohibit fruit growers from producing their own transplants.
Economic Differences	
There is considerable variation in soil-less systems being used for the production of plugs. The economics therefore varied, but plug plants were still at least 1.4 times more expensive that bare-rooted runners produced in fumigated soil. Plug plants generally yield higher than bare-rooted runners, which justifies their increased cost.	Cost increases for plug plants in Australia are not accepted by fruit growers because they do not currently yield as consistently well as bare-rooted runners (Menzel & Toldi, 2010).
Labour costs were reported at A$1.50/hour.	Labour costs are A$24/hour.

6.2.3 Research on Soil-less Systems

6.2.3.1 Transplant production

Hydroponic production in a screenhouse produced significantly more transplants (up to 88% more) than the same system outdoors (e.g. Figure 16). Under screenhouse conditions, yields of transplants of most cultivars tested were significantly higher (by up to 90%) in the hydroponic systems than those in large bins containing substrate. Yields were also significantly higher (by up to 96%) for most cultivars in the hydroponic system in the screenhouse compared with field production in soils treated with MB/Pic.

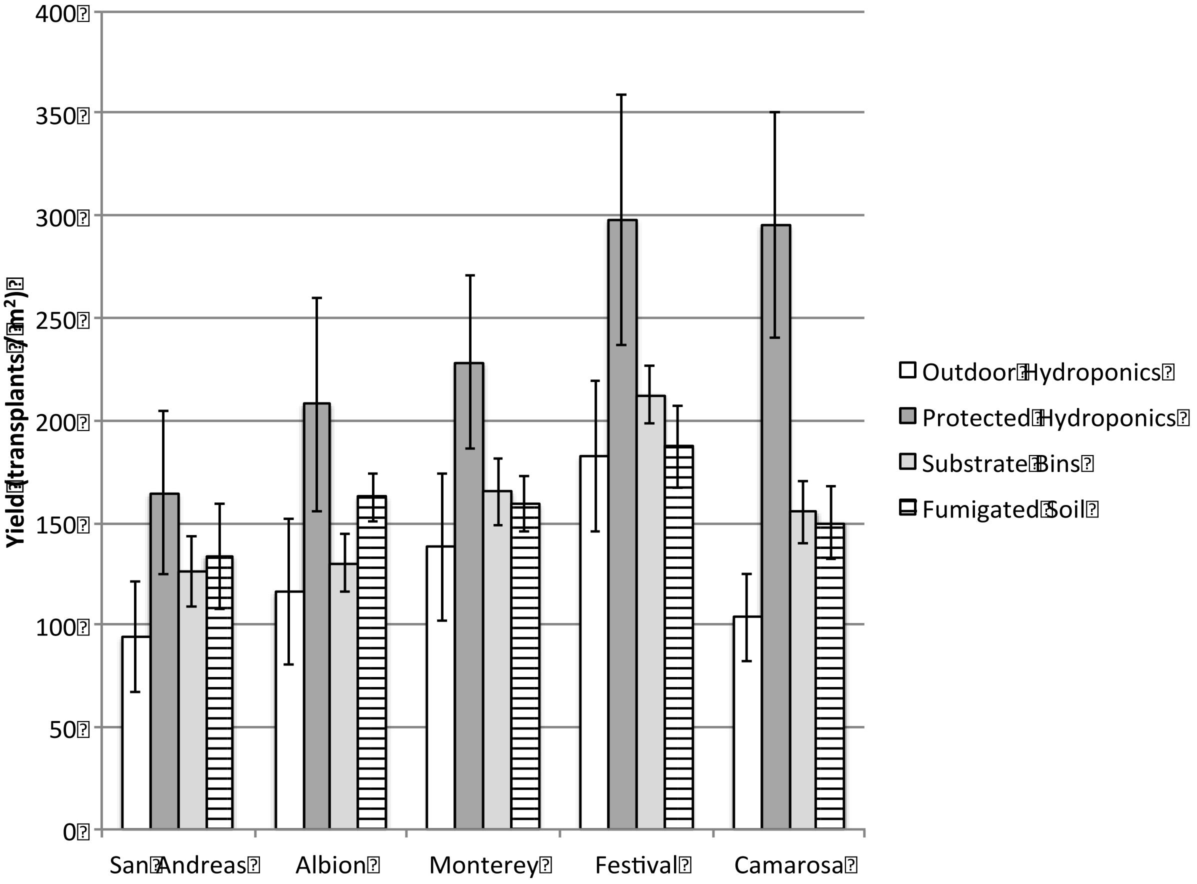

Figure 16. *Transplant yields (transplants/m^2) of strawberry cultivars in soil-less systems and in field soil treated with MB/Pic (500 kg/ha) at Toolangi, Victoria in 2014/15. Bars represent 95% confidence intervals.*

6.2.3.2 Yields of plug plants in the runner industry

In most fumigant treatments, runner yields from plug plants were significantly higher than those from bare-rooted runners (Figure 17). In soils treated with MB/Pic, however, plug plants and bare-rooted runners produced equivalent runner yields. Plug plants grown in soils treated with 1,3-D/Pic (20:80) produced equivalent runner yields to bare-rooted mother plants grown in soils treated with MB/Pic (Figure 17).

6.2.3.3 Yields of plug plants in the fruit industry

Fruit yields from plug plants produced in the hydroponic system in the screenhouse were highly variable across Australia. At Wanneroo, Western Australia, plug plants produced significantly less fruit (up to 40% less) than bare-rooted runners (Figure 18). This was equivalent to a loss in revenue from fruit of 42%, or $2.68 less per plant. At Millgrove Victoria, however, plug plants produced significantly more fruit than bare-rooted runners (22% more) (Figure 19). This was equivalent to an increase in revenue from fruit of 23%, or $1.10 more per plant.

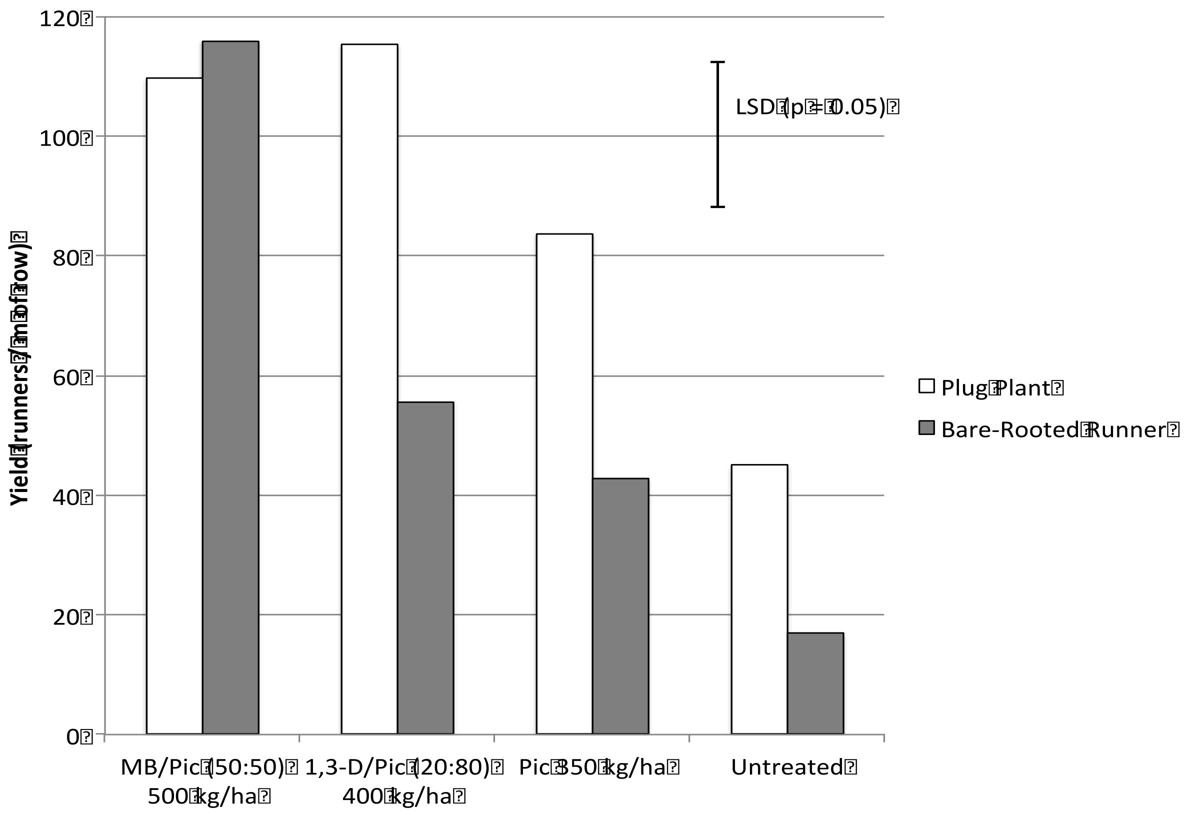

Figure 17. *Commercial yields (runners / m of row) from plug plant and bare-rooted mothers of strawberry (cv. San Andreas) grown in soil treated with different fumigant treatments at Toolangi, Victoria in 2014/15. The bar represents the least significant difference where p = 0.05.*

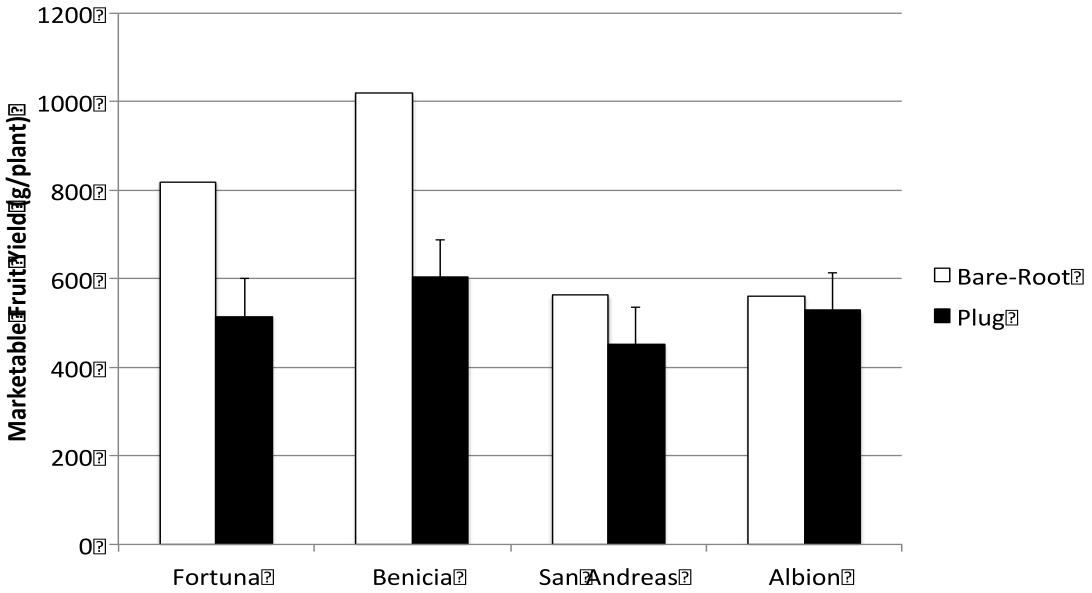

Figure 18. *Total fruit yields of different cultivars of strawberry grown from bare-rooted runners or plug plants in a field trial at Wanneroo, Western Australia in 2015. The bars represent the least significant difference where p = 0.05.*

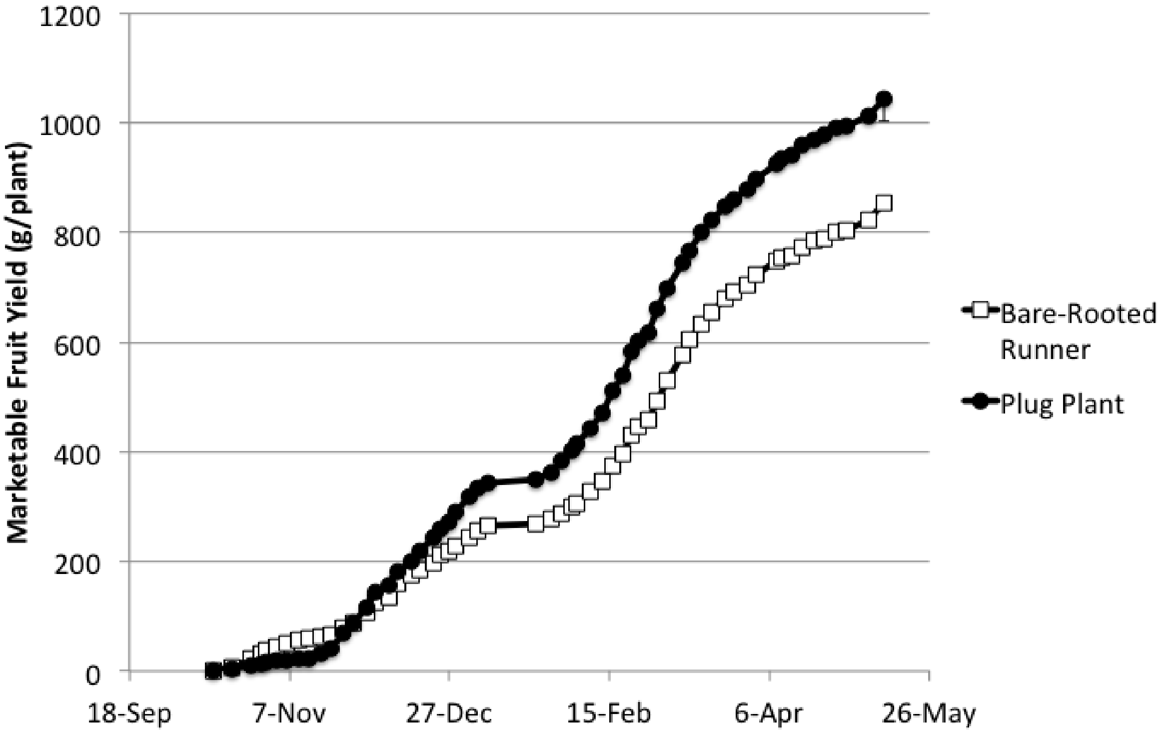

Figure 19. *Cumulative fruit yields of strawberry (cv. Albion) grown from bare-rooted runners or plug plants in a field trial at Millgrove, Victoria in 2014/15. The bar represents the least significant difference where p = 0.05.*

7. Evaluation and Discussion

7.1 Discussion:

7.1.1 Integrated Soil Disinfestation Systems

Of the 102 different combinations of substitute fumigants, herbicides and fungicides investigated in this project, none controlled pathogens, weeds and produced runner yields to the same level as MB/Pic. Despite this, research made considerable progress towards the development of integrated soil disinfestation systems as substitutes to MB/Pic. At the beginning of this project, crop phytotoxicity and poor weed control were two of the important issues preventing the successful adoption of substitute fumigants and forcing the strawberry runner industry to apply for critical-use exemptions for MB. This project developed potential strategies for runner growers to manage these issues. For example, research demonstrated that 1,3-D/Pic formulations containing low concentrations of 1,3-D (i.e. 1,3-D/Pic (20:80)) had short residence and plant-back times in soils at Toolangi, and therefore reduced the risk of crop phytotoxicity. Furthermore, research identified that co-application of specific pre- and post-emergent herbicides (isoxaben, phenmedipham and fluazifop-p) with 1,3-D/Pic (20:80) managed weeds to similar levels as MB/Pic, without reducing runner yields. Other substitute fumigants (e.g. EDN and DMDS/Pic) applied with these herbicides also showed the capacity to control weeds and produce runner yields equivalent to MB/Pic. However, none of these substitute fumigants (except 1,3-D/Pic (20:80)) and herbicides (except fluazifop-p) is currently registered or available for use by the runner industry.

The most significant problem with substitute fumigants was their failure to control soil-borne pathogens as well as MB/Pic. A high level of control of pathogens in strawberry nurseries is essential to maintain phytosanitary standards and support market access of runners from region to region. Of the substitute fumigants investigated, research showed that 1,3-D/Pic (20:80) provided the best control of soil-borne pathogens. This fumigant did not, however, adequately control soil-borne pathogens deep in the soil profile. By the time of runner harvest, pathogens had recolonised the upper profile in soils treated with 1,3-D/Pic (20:80), and populations were no different to those in untreated soils (and significantly higher than soils treated with MB/Pic). Deeper injection and application under virtually impermeable barrier film did not improve pathogen control with 1,3-D/Pic (20:80). In contrast, deeper injection under virtually impermeable film did improve pathogen control by the substitute fumigant EDN, but not to the same level as MB/Pic.

Co-application of the methyl isothiocyanate generators, Daz and MS, showed the capacity to improve pathogen control with the substitute fumigants 1,3-D/Pic (20:80) and DMDS/Pic. However, these combinations also killed or severely stunted strawberry plants. Residues of methyl isothiocyanate persisted in soils at Toolangi for 126 days and required long plant-back times of over 3 months, even when treated in warmer temperatures in Spring. This means that Daz and MS would be particularly difficult for growers to implement in their rotation systems in the Victorian runner industry, unless they are applied well before other fumigant treatments.

A potential consequence of poor pathogen control with substitute fumigants in the runner industry is lower yields in the fruit industry. In trials in the fruit industry in contrasting locations around Australia, runners produced in soils treated with substitute fumigant systems in the nursery industry produced less fruit than those produced in soils treated with MB/Pic in the nursery (9 – 15% less, equivalent to 10 – 16% less revenue from fruit). In one trial in the fruit industry, strawberry plants from runners produced in soils treated with substitute fumigants had higher incidence of black root rot and recovery of *Pythium* pathogens than plants from runners produced in MB/Pic-treated soils. Furthermore, these higher disease levels were associated with lower yields of fruit. These results generally concur with previous estimates that the loss of MB/Pic without a suitable substitute would result in yield losses in the fruit industry of up to 15%, worth $30-60 M p.a. (BS01004). This demonstrates that the impact of the loss of MB from the runner industry, without an effective substitute, is likely to be greater on the fruit industry than on the nurseries.

Further research urgently needs to be conducted on methods to improve control of pathogens using substitute fumigant / herbicide systems in the runner industry, including:

1. Deeper application (up to 30 cm) of substitute fumigants to control pathogens deeper in the soil profile.
2. Formulation or co-application of some substitute fumigants (e.g. EDN and DMDS) with higher concentrations of Pic. This is because Pic is highly active against fungal pathogens (Desmachelier and Vu, 1998).
3. Further evaluation of totally impermeable films, to increase exposure times of pathogens to substitute fumigants.
4. Application of methyl isothiocyanate generating fumigants well before (6 months) co-application with other substitute fumigants.
5. Higher dosage rates of key substitute fumigants in experimental settings.
6. Integration of biofumigant cropping practices with the use of substitute fumigants.
7. Different combinations of fungicides co-applied with substitute fumigants.
8. Development of bystander safety and environmental emission data to further support the registration of some substitute fumigants.
9. Evaluation of new substitute fumigants (e.g. propylene oxide and propylene oxide / Pic).
10. Commercial trials investigating runner production in different locations around Australia that may have soil-types more suited to the use of substitute fumigants.

The Victorian runner industry may need to consider further applications for critical-use exemptions for MB while this research occurs.

7.1.2 Soil-less Systems

Soil-less methods of production have so far proven too costly, compared with bare-rooted runner production in the field, for full adoption by the Australian strawberry nursery industry (Menzel et al., 2010; Mattner et al., 2014; Mattner et al., 2016a). For example, partial budget analysis showed that operating profit margins for production of bare-rooted Mother (third generation) and Certified (fourth generation) runners would decrease from 8% in MB/Pic-treated soil to -83% in soil-less substrates, and therefore is not economically viable. The increased cost of bare-rooted runners produced in soil-less substrates is mostly due to high infrastructure and labour costs. However, soil-less technologies are viable for use in the early generations of runner multiplication, where plants have their highest value.

Results from this project showed that protected hydroponic systems for the production of plug plants were highly efficient, in terms of transplant yields per unit area, for early generations of strawberry runners. Despite being cheaper, outdoor hydroponics systems were less efficient for production of transplants and exposed plants to the risk of infection by pathogens such as viruses and phytoplasmas transmitted by insects. For these reasons, protected systems are currently considered the most suitable for production of the early generations of runners. The Victorian runner industry has adopted soil-less systems for the production of the first two generations (Nucleus and Foundation stock) in the multiplication scheme.

Prior to this project, the performance of plug plants for runner production had not been evaluated in Australia. Results showed that plug plants produced higher yields of runners than bare-rooted mother plants, when grown in soils treated with substitute fumigants to MB/Pic. This was most likely due to the earlier stolon growth of plug plants compared with bare-rooted runners, which provided cover and competed better with the high populations of weeds in soils treated with substitute fumigants. Plug plants grown in soils treated with the substitute fumigant 1,3-D/Pic (20:80) produced equivalent yields of runners to bare-rooted mother plants grown in soils treated with MB/Pic. However, further research is needed on methods and integrated treatments to improve control of soil-borne pathogens with 1,3-D/Pic (20:80) (see above). Nonetheless, the use of plug plants combined with substitute fumigants to MB/Pic, and other integrated treatments, warrants further investigation as a substitute system to MB/Pic for runner production.

Previous research in Australia has evaluated the suitability of plug plants for strawberry fruit production. Studies generally showed that plug plants did not produce higher or earlier fruit yields than bare-rooted runners (Menzel and Waite, 2006; Menzel et al., 2010; Mattner et al., 2016a). In the current project, research showed that yields of fruit from plug plants were highly variable compared with bare-rooted runners produced in MB/Pic-treated soil (ranging from producing 23% more fruit to 40% less fruit). Plug plants would need to produce consistently higher and/or earlier yields to justify their increased cost and adoption by the fruit industry. Further research is needed on the physiology of plug plants and their possible conditioning to achieve more consistent and higher fruit yields, before they could be considered a technically and economically feasible option to production of bare-rooted runners in MB/Pic-treated soils.

7.2 Impact, Consequences, and Evaluation:

At the beginning of this project, the anticipated outcomes from the research program were:

(1) Industry has an internationally recognised R&D program that allows continued nominations for MB under critical-use exemptions in the runner industry, and prevents reductions in profits for the fruit industry, while viable alternatives are being developed.

Achieved.

Immediately following approval of this project, the Victorian runner industry was in full compliance with Decision IX/6 under the *Montreal Protocol* because an approved R&D program to identify substitutes to MB was in place. This led to critical-use exemptions for the use of MB in the Victorian runner industry being fully re-instated in 2015, while research progressed on technically and economically feasible substitutes. It also allowed the runner industry to apply for four further nominations for critical-use exemptions for MB in 2016 (approved), 2017 (approved), 2018 (approved), and 2019 (under consideration) because research in this project showed that the runner industry does not currently have technically or economically feasible substitutes available. This has prevented yield and revenue losses in the fruit industry initially estimated at up to 15% and $60 M p.a. (see above), while research on identifying viable substitutes for the runner industry continued.

(2) Federal and state government make considered assessment of the quarantine status of MB use in the runner industry. This provides time for the development of suitable substitutes to MB if approval is granted.

Partially Achieved.

In meetings organised and facilitated through this project, federal and state government have considered whether the current use of MB in the strawberry runner industry qualifies as a quarantine application, which is exempt from phase-out. As a result, federal government (Department of Agriculture and Water Resources) provided the runner industry with a framework to apply for a quarantine exemption for MB. A draft application was prepared based on this protocol, and submitted to the runner industry for consideration. Currently, federal and state government agencies in Australia do not consider the use of MB in the runner industry a quarantine application, as is the case in the USA.

(3) MB is phased out in the strawberry runner industry if soil disinfestation or soil-less production systems are developed that are technically feasible, effective, economically viable, and meet current certification standards.

Partially achieved.

Research and analysis in this project showed that there are currently no technically or economically feasible substitutes to MB/Pic available to the runner industry. This research allowed the industry to apply for critical-use exemptions for MB from the UN, while research continued on identifying more suitable substitutes. This has saved the fruit industry from anticipated losses of up to $60 M p.a. (see above).

Despite the lack of immediate substitutes, research made considerable progress towards the development of substitute systems to replace MB/Pic. For example, it identified more efficient soil-less systems for production of plug plants (hydroponics). These systems are now partially adopted by the Victorian runner industry for production of the Foundation stock (second generation runners) and, with further evaluation and development, may be suited to Mother stock (third generation runners) production.

At the beginning of this project, crop phytotoxicity and poor weed control were two important issues preventing the successful adoption of substitute fumigants by the Victorian runner industry. Research developed potential strategies for runner growers to manage these issues, including the use of 1,3-D/Pic formulations containing low concentrations of 1,3-D (i.e. 1,3-D/Pic (20:80)), and the integrated use of specific pre- and post-emergent herbicides with key substitute fumigants. The remaining issue is less effective control of soil-borne pathogens with substitute fumigants compared with MB/Pic. This project developed a 10-point research plan aimed at resolving the issue of poor pathogen control with substitute fumigant systems (see Discussion above). Based on this research plan, current research progress, and the anticipated registration of key substitute fumigants, industry has developed a transition plan to phase-out MB, and presented this to plan the federal government agencies and the United Nations.

Other outcomes resulting or supported by this project include:

1. All Victorian runner growers have commenced commercial-scale trialling and practising production with substitute fumigants and herbicides in preparation for their eventual registration and use. Runners from these blocks will not be Certified and sold.
2. Data from this project supported the successful registration of 1,3-D/Pic (20:80) (TriForm80®) in Australia in 2016, not only for runner growers, but also for strawberry fruit and other horticultural industries.
3. Chemical companies are using data from this project to support registration applications for other key substitute fumigants (including EDN and DMDS).
4. New fumigants (DMDS and DMDS/Pic) were imported into Australia for trial and registration purposes.
5. New barrier films (VIFs and TIFs) for soil fumigation are imported and available commercially through fumigant contractors. For the first time in Australia, local plastics manufacturers have imported equipment and commenced manufacture of TIF for use in Australian horticulture.
6. Spading rigs for improved application of MS are imported and available commercially to horticultural growers through fumigant contractors.
7. Hydroponic systems for production of plug plants are adopted for the production of Foundation stock (second generation runners), and the runner industry is currently constructing prototype systems for evaluation of hydroponics for later generations of runners.
8. The runner industry is commercially producing plug plants from tips produced in MB/Pic-treated soils, for widespread evaluation trials across the strawberry fruit industry.

Together, these outcomes demonstrate uptake and use of information and outputs from this project by industry, chemical companies, plastics manufacturers, fumigant contractors, and government.

Apart from achieving significant outcomes for industry (see above), the effectiveness and quality of the research in this project can also be measured by:

1. The production of five refereed publications (see 'Scientific Refereed Publications'), and the prospect of developing further journal papers after the completion of the project.
2. Invitations from the conveners of the International Convention and Exhibition on Soil-less Culture and Asia-Pacific Seed Congress to present research from the project as opening and keynote addresses.
3. A request from the Victorian Branch of the Australasian Plant Pathology Society to tour the nursery industry and research sites within this project.

In addition to research, this project also conducted a communication program that delivered an average of more than one activity or output per month to strawberry growers (see 'Outputs'). Key components of the communication program that proved particularly successful included:

1. Conducting research trials, field days and meetings on growers' properties. This allowed growers to review the results and outcomes of research through oral presentations, assess the performance of treatments in the field, and to provide direct feedback on research directions and treatments. An example of grower input into the research was the concept of calculating the revenue through the season from different treatments in evaluation trials in the fruit industry.
2. Conducting study tours for runner growers of overseas nursery industries (Japan, Europe, South Africa) that have already transitioned or partially transitioned away from the use of MB/Pic. Growers provided rapid evaluation of methods used overseas for their practicality and

suitability for adoption into the Victorian runner industry. For example, specific features of hydroponics systems used overseas were immediately captured and incorporated into prototype designs evaluated in this project. This approach fast-tracked and maximised the efficiency of the hydroponic systems constructed in this project, and allowed their evaluation using world's best practices.

Work in this project contributed to the project team being presented the 2016 Industry Award from the Victorian Strawberry Growers Association for recognition and appreciation of efforts to the strawberry industry.

8. Recommendations

8.1 Recommendations to the Strawberry Runner Industry:

1. Currently substitute fumigants and integrated soil disinfestation systems do not control soil-borne pathogens as well as MB/Pic. Industry needs to continue to support ongoing research aimed at improving pathogen control with substitute soil disinfestation systems. Industry should consider continued applications for critical-use exemptions for MB following the transition plan developed through this project, while further research is undertaken and key substitute fumigants are undergoing registration in Australia. If successful, this move would safeguard the strawberry fruit industry from expected losses in yield (15%) and income ($60 M p.a.), while substitute systems to MB for the runner industry are in development.

2. If ongoing research fails to identify methods to improve control of soil-borne pathogens with substitute fumigants to MB/Pic, the runner industry should consider submitting an application to federal and state governments requesting a re-classification of the use of MB/Pic for soil disinfestation in the runner industry to a quarantine application. This would exempt MB from phase-out, and allow additional time for further research to develop more suitable substitutes for MB/Pic.

3. Industry needs to further consider the possibility of moving to other areas in Australia that may have soil types and environments that are better suited to the use of substitute fumigants. This would require industry to undertake commercial runner trials with substitute fumigants in different regions of Australia with lighter soil types than those at Toolangi, Victoria. It would also involve evaluation trials in the fruit industry to prove that runners grown at these alternate locations produce the same fruit yields as those grown in soils treated with MB/Pic at Toolangi. Finally, it would require a detailed analysis of the economic, social, and environmental costs of potentially moving the runner industry from Toolangi to an alternate location.

4. If the above recommendations fail, the runner industry needs to further consider potential litigation risks, and the viability of the industry in Australia in the medium to longer term.

8.2 Recommendations to the Victorian Strawberry Industry Certification Authority (VSICA):

5. Soil disinfestation with MB/Pic has been very successful in enabling runner crops in Victoria to meet the certification standards for the incidence of symptoms of soil-borne diseases. However, VSICA needs to consider how it will certify runners following the phase-out of MB. Research in this and previous projects has quantified DNA concentrations of key pathogens in soil at Toolangi, Victoria following treatment with MB/Pic. One option for runner certification in the future is to develop soil-sampling strategies and set thresholds for key pathogens based on concentrations measured in MB/Pic-treated soils (e.g. 0 pg DNA/g soil for *Macrophomina phaseolina* at planting).

8.3 Recommendations to the Strawberry Fruit Industry:

6. The loss of MB/Pic from strawberry nurseries, without a suitable substitute, will have a greater impact on the strawberry fruit industry than on the runner industry. This project showed that the use of the best substitute fumigants currently available to the runner industry would result in yield losses of fruit of between 9 - 15%, and revenue losses from fruit of 10 – 16% (equivalent to up to $60 M p.a). Evidence showed that these losses in the fruit yield were associated with higher levels of soil-borne pathogens in runners. The strawberry fruit industry needs to consider whether a greater proportion of its levy funds should be directed towards improving control of soil-borne pathogens using substitutes to MB/Pic in the runner industry, in order to maintain current productivity and profit levels in the fruit industry.

8.4 Recommendations to Government:

7. The use of MB to treat strawberry fruit imported from overseas is approved in Australia, under a quarantine exemption, to prevent biosecurity threats from pathogens and pests entering this country. Some of the countries that Australia currently imports strawberry fruit from still have access to MB for soil disinfestation in their runner industries, under a quarantine exemption (e.g. USA). However, MB is not currently approved for use in the Australian runner industry under a quarantine exemption, even though it is now primarily used to prevent the spread of soil-borne pathogens from state to state. The Australian strawberry fruit industry is worth $450 M p.a. to the national economy, allied industries are worth an estimated $300 M p.a., and the fruit industry supports over 15,000 full-time and temporary jobs. There is no difference in the impact of quarantine and non-quarantine MB on the environment. An environmental impact analysis is therefore warranted on the use of MB for importing strawberry fruit from countries that still use MB for soil disinfestation, compared with the small amounts currently used in Victorian strawberry nurseries to support the health and viability of the national industry.

8.5 Recommendations to HIA Limited:

8. This project has demonstrated that great benefits for the whole of the strawberry industry can occur from research and development applied at a regional level (i.e. Toolangi Victoria). This project was funded through industry voluntary contributions matched by government money. The new funding structure of HIA Limited may present a challenge in the future because there is no longer a clear pathway to support industry-specific research through matched voluntary contributions, especially at a regional level. The future funding of research projects that are regionally significant, but have wider impacts, requires further consideration by the strawberry industry and HIA Limited.

The chemicals Pic, MS, Daz and 1,3-D/Pic (100:0, 65:35, 40:60 and 20:80) are currently registered for use as pre-plant treatments for soils in Australia. The chemical MB/Pic is currently registered for *use as a pre-plant treatment for soil to holders of a critical-use permit or for approved quarantine uses. The chemicals fluazifop-p and chlorthal-dimethtyl are currently registered for use in strawberry crops. None of the other chemicals used in this project are currently registered for use in strawberry runner production in Australia. The up-to-date list of registered products and permits for strawberry runner production is available on the Australian Pesticide and Veterinary Medicine Authority (AVPMA) website (http://www.apvma.gov.au).*

9. Scientific Refereed Publications

Mattner, S.W., Horstra, C.B., Milinkovic, M., Merriman, P.R., Greenhalgh, F.C., 2016. Evaluation of soil-less systems for strawberry transplant production. *Acta Horticulturae* (in press).

Mattner, S.W., Milinkovic, M., Merriman, P.R., Porter, I.J., 2014. Critical challenges for the phase-out of methyl bromide in the Australian strawberry industry. *Acta Horticulturae* **1044**, 367-373.

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10. Intellectual Property/Commercialisation

No commercial IP generated.

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12. Acknowledgements

The project team acknowledges the in-kind support and assistance from growers who hosted trials, chemical companies (Arkema, BOC, and TriCal), and fumigant contractors (R&R Fumigation Services).

13. Appendix

Appendix I: Mattner S.W., et al., 2015. Integrated Weed Control in the Strawberry Runner Industry with Herbicides and Fumigants. Best Practice Flyer, VSICA, Toolangi, Victoria.

INTEGRATED WEED CONTROL IN THE STRAWBERRY RUNNER INDUSTRY WITH HERBICIDES AND FUMIGANTS

Background

Currently, the strawberry runner industry at Toolangi uses mixtures of methyl bromide (MB) and chloropicrin (Pic) to control soil-borne diseases, weeds and pests. MB is highly effective for weed control, but the *Montreal Protocol* has listed it for phase-out. Ultimately, the runner industry at Toolangi will need to use substitute products for MB/Pic to treat soils.

Previous research shows that many substitute fumigants do not control weeds as effectively as MB/Pic. In the future, runner growers may need to consider co-application of herbicides and substitute fumigants to manage weeds.

Figure 1: Symptoms of phytotoxicity in strawberry plants (cv. Monterey) treated with the pre-emergent herbicides Goal® (left) and Sinbar® (right). The pre-emergent herbicide Gallery® did not cause phytotoxicity in strawberry plants in trials at Toolangi.

Pre-Emergent Herbicides

Research in the USA has screened a number of pre-emergent herbicides for use in strawberries. The most promising products from this research were evaluated in trials at Toolangi in the runner industry in 2013/14. Herbicides were applied immediately following planting to soils previously treated with different fumigants.

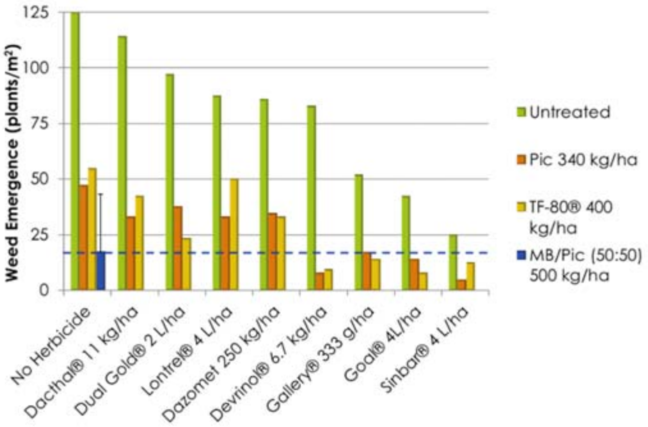

Figure 2: Weed emergence in soils treated with different fumigants and pre-emergent herbicides in the strawberry runner industry at Toolangi (2013/14). The blue dashed line represents weed emergence in soils treated with the standard MB/Pic treatment.

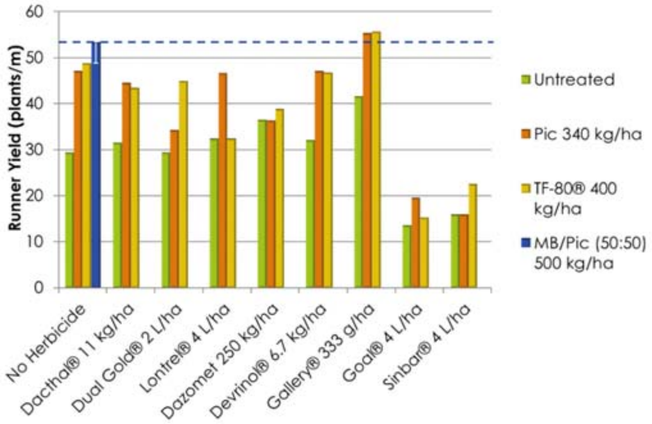

Figure 3: Strawberry runner yields (cv. Monterey) in soils treated with different fumigants and herbicides at Toolangi (2013/14). The blue dashed line represents runner yields in soils treated with the standard MB/Pic treatment. Some pre-emergent herbicides (particularly Dual® and Sinbar®) caused symptoms of phytotoxicity and low yields in runner crops. Gallery® was the most successful pre-emergent herbicide in the trial for weed control and high strawberry yields.

Most of the pre-emergent herbicides tested caused phytotoxicity, stunting, and/or poor runner yields of strawberry plants (Figure 1). The herbicide Gallery® (isoxaben), however, improved weed control and increased strawberry yields. Co-application of Gallery® and the fumigant TF-80® (20% 1,3-dichloropropene (1,3-D): 80% Pic) and PicPlus® gave equivalent weed control and runner yields to MB/Pic (Figure 2 & 3).

Post-Emergent Herbicides

Runner growers in the Netherlands use regular applications of post-emergent herbicides, such as Betanal® (phenmedipham) and Fusilade® (fluazifop-p-butyl), for weed control. Trials were conducted at Toolangi in 2014/15 to evaluate the use of pre- and post-emergent herbicides with substitute fumigants for weed control. Post-emergent herbicides were applied to strawberry runners on a fortnightly basis.

Figure 4: Application of the granular fumigant dazomet (left), and the liquid fumigant metham sodium (right) in the runner industry at Toolangi. These fumigants have strong herbicidal properties and can be co-applied with other fumigants (e.g. TF-80®) for improved weed control. Dazomet and metham sodium have long residual times in soils at Toolangi and would require application well before planting (late summer – early autumn) to ensure crop safety.

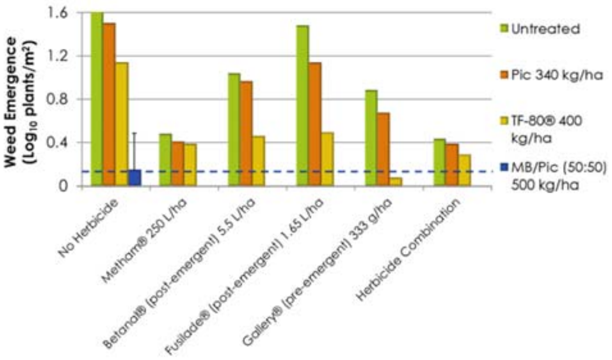

Figure 5: Weed emergence in soils treated with different fumigants and pre- and post-emergent herbicides in the strawberry runner industry at Toolangi (2014/15). The 'Herbicide Combination' included Gallery® pre-emergent, and Betanal® and Fusilade® post-emergent treatments. The blue dashed line represents weed emergence in soils treated with the standard MB/Pic treatment.

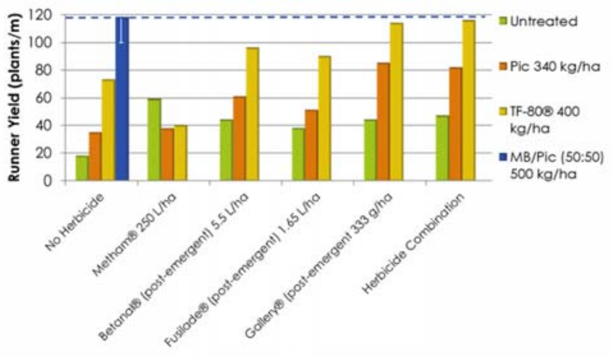

Figure 6: Strawberry runner yields (cv. San Andreas) in soils treated with different fumigants and pre- and post-emergent herbicides at Toolangi (2014/15). The 'Herbicide Combination' included Gallery® pre-emergent, and Betanal® and Fusilade® post-emergent treatments. The blue dashed line represents runner yields in soils treated with the standard MB/Pic treatment.

Results showed that post-emergent herbicides controlled weeds compared with no application of herbicides. They caused some symptoms of phytotoxicity to strawberry plants, but did not reduce their yields. Co-application of pre- and post-emergent herbicides gave no better weed control than pre-emergent herbicides applied alone (Figure 5). Co-application of herbicides with TF-80® gave equivalent runner yields and weed control to MB/Pic (Figures 5, 6 & 8).

Co-Application of Fumigants

Some substitute fumigants to MB/Pic, such as metham sodium and dazomet (methyl isothiocyanate (MITC) generators) have herbicidal properties (Figure 4). Trials at Toolangi investigated co-application of MITC generators with other substitute fumigants. Results showed that co-application of metham or dazomet with TF-80® or PicPlus® improved weed (Figures 2 & 5) and soil-borne pathogen control. However, metham and dazomet had very long residual times in soil at Toolangi (3 months), and caused significant yield losses in strawberry runners (Figures 3 & 6). This means that growers would need to apply these products early (late summer – early autumn), and measure MITC levels in soil before planting (Figure 7) to minimise the risk of phytotoxicity with this approach.

Note: MITC generators are highly reactive when mixed with many substitute fumigants. This means they **must** be applied in separate operations for safety reasons.

Conclusions

The ultimate withdrawal of MB/Pic and the lower effectiveness of substitute fumigants means that runner growers will need additional methods to manage weeds. This will require greater consideration of cropping rotations (e.g. biofumigant crops), herbicide treatments during fallow periods, and the possible co-application of herbicides and substitute fumigants before and during runner production. Results from trials at Toolangi showed that co-application of the pre-emergent herbicide Gallery® and TF-80® provided good weed control and runner yields. These products, however, are **not** currently registered for use on strawberry runners. Chemical companies are using data from trials at Toolangi to support possible registration or permits for these products. Scientific and commercial trials evaluating the co-application of substitute fumigants and herbicides in the runner industry are continuing at Toolangi.

Figure 7: Measuring residues of dazomet and metham sodium in soil using Gastec® tubes.

Many of the chemicals used in these experiments are **not** presently registered for use on strawberry plants in Australia. The list of registered products and permits for strawberry runner and fruit production are available on the APVMA website (www.apvma.com.au). The product label is the official authority and should always be followed in relation to the use of a chemical.

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Disclaimer

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For further information contact Dr Scott Mattner from VSICA (swmattner@hotmail.com).

Figure 8: Weed emergence and strawberry runner growth (cv. San Andreas) in selected plots treated with different fumigants and herbicides in a field trial at Toolangi (2014/15).