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Risk-based fungicide management for myrtle rust in nurseries

Beresford RM, Wright PJ

July 2022

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DISCLAIMER

This report is intended to support myrtle rust control in nurseries only, following product use guidelines for safe application by trained professionals. It does not seek to promote fungicide use in natural estate, home gardens or other environments where the risks of fungicide application have not been properly assessed, and inadequate product use could threaten human or animal health and the environment.

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Risk-based fungicide management for myrtle rust in nurseries

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Introduction

Myrtle rust affects the production of some vulnerable native and exotic species in the Myrtaceae (myrtle family) in plant nurseries and requirements for controlling this disease are not yet fully understood. This project, funded by the Ministry for Primary Industries (MPI), sought to help New Zealand Plant Producers Incorporated (NZPPI) develop a structured approach for optimising use of fungicides against myrtle rust in nurseries. As no fungicide products are currently registered specifically for myrtle rust control in New Zealand, all fungicides are used under the conditions of 'off-label use'. See Off-Label use of Agrichemicals-NZGAP Guideline for Growers v1.5 (Dec 2021).pdf for explanation of the requirements for off-label use.

The project utilised an online weather-risk tool (NZPPI Plant Disease Management Platform | Myrtle Rust Cumulative Risk (metwatch.nz)), currently being developed by The New Zealand Institute for Plant and Food Research Limited (PFR), HortPlus Ltd and NZPPI, to target fungicides according to measured risk. There were three objectives:

1. Compare risk-based and calendar spraying strategies using single-site inhibitor and multi-site inhibitor mode of action fungicides (see Glossary of fungicide-related terms in Appendix 3).
2. Develop a weather-risk tool for spray management using the PFR/HortPlus climatic risk tool being developed for NZPPI to decide optimal spray timing.
3. Develop fungicide resistance prevention guidelines in conjunction with NZPPI.

During the field fungicide trials to address Objective 1 and develop the weather-risk tool for Objective 2, it became clear other considerations affecting myrtle rust fungicide programmes also needed to be addressed. These were: myrtle species vulnerability, seasonal growth flush, sources of infection, regional and seasonal variation in climatic risk and the required application frequency of different fungicide types. To address these an additional objective is included in this report:

4. Develop recommendations on risk factors that affect the design of myrtle rust spray programmes in New Zealand nurseries.

Fungicide spray trials

- Two replicated trials using potted plants of myrtle rust-vulnerable *Lophomyrtus* sp. cultivar ‘Red Dragon’ compared different fungicide products applied according to either weather-risk tool indications or calendar spraying every 14 days.
- NZPPI-recommended fungicides were used, including five with single-site inhibitor mode of action, from the demethylation inhibitor (DMI; Group 3), quinone outside inhibitor (QoI; Group 11) and succinate dehydrogenase inhibitor (SDHI; Group 7) fungicide groups, and two multi-site inhibitor broad-spectrum fungicides, copper hydroxide (Group M1) and mancozeb (Group M3). The first trial was conducted during summer 2021–22 and the second during autumn 2022.
- Rust control and growth flush protection were greatest for the DMIs, triadimenol (Vandia®) and myclobutanil (Validus®), and the QoIs, trifloxystrobin (Flint®) and pyraclostrobin (Comet®), were also very effective. Copper hydroxide (Kocide® Opti™) and mancozeb were not significantly different from the nil-fungicide treatment. The SDHI, fluxapyroxad, was used as two formulations (Sercadis® and Imtrex®) and at two application rates but neither was more effective than copper hydroxide or mancozeb.
- Use of the weather-risk tool in Trial 1, during warm summer conditions, resulted in more fungicide applications than 14-day calendar spraying (nine compared with six) and in Trial 2, during cooler autumn conditions, it resulted in fewer applications (four compared with six). Differences in disease control between the two spray timing strategies were mostly not statistically significant. Spray re-application intervals for weather-risk timing ranged from 6 days during high-risk periods in summer to 33 days during low-risk periods in late autumn.
- The following conclusions were drawn from the fungicide trials:
    - Single-site inhibitor Group 3 DMI fungicides have the highest efficacy against myrtle rust and the Group 11 QoI fungicides are also highly effective. The Group 7 SDHI fungicide fluxapoyroxad had poor efficacy.
    - Further testing is required of Group 7 SDHI efficacy against myrtle rust, including benzodiflupyr (Elatus® Plus), which is also recommended by NZPPI.
    - The low efficacy of copper hydroxide and mancozeb would require them to be used at short re-application intervals.
    - Risk-based spraying using the weather-risk tool successfully demonstrated a practical way for sprays to be targeted when they are most needed in different seasons.
    - Further refinement of the weather-risk tool is needed to define spraying thresholds appropriate for fungicides with different degrees of efficacy.

Accuracy of weather forecasts for timing sprays

- The weather-risk tool includes weather forecasts (provided by IBM) up to 14 days ahead to calculate future myrtle rust weather risk and allow spray planning in advance.
- Analyses showed forecast accuracy to be adequate for making correct spray decisions 1–3 days ahead but more than 4–6 days ahead it is inadequate. However, the longer-range forecasts are still useful for identifying incoming weather systems that could generate periods of high risk.
- Further work is needed to develop a way for weather-risk tool users to understand the degree of confidence they can have in each day’s forecast as it is received.

Resistance management guideline for myrtle rust

- Fungicides in mode of action groups 3 DMI, 7 SDHI and 11 QoI are suitable for controlling myrtle rust but are at risk from resistance. These should be used as follows:
    1. Apply preventatively when disease risk is high and preferably before disease appears.
    2. Make no more than five applications of each at-risk group per year (1 July – 30 June).
    3. Apply each at-risk fungicide either in mixture with an effective dose of a multi-site inhibitor (groups M1, M3 and M5) or in strict alternation with either a single-site fungicide in a different group or, preferably, a multi-site fungicide.
    4. When choosing fungicides, make use of the group codes displayed on product labels to avoid mixed or consecutive applications of the same at-risk mode of action group.
    5. The application rate of a fungicide used for myrtle rust control should be the recommended label rate for that fungicide on an appropriate other crop (Ministry for Primary Industries - ACVM Register (nzfsa.govt.nz)).
    6. An application of a product containing a mixture of two fungicides in the same mode of action group counts as one application towards that group's annual count.
    7. The Environmental Protection Authority (EPA) may specify a maximum number of applications per year for particular fungicide products. This takes priority over maximum numbers indicated in this resistance management guideline for any so-specified product. (Controls for hazardous substances | EPA).
  - This guideline has been reviewed by the New Zealand Committee on Pesticide Resistance.

Myrtle rust spray programme design

A nursery fungicide spray programme against myrtle rust must consider the following risk factors:

1. Vulnerability of different myrtle species.
2. Presence of shoot flush on vulnerable species.
3. Nearby sources of infection.
4. Climatic risk, regionally, seasonally and daily.
5. Selection of appropriate fungicides.
6. Fungicide resistance management to limit the use of certain fungicide groups.

The influence of each factor on spraying requirements was examined and from this, national spraying requirements for different regions and seasons were modelled using output from the weather-risk tool.

1. **Species vulnerability** varies for both native and exotic myrtles and the general impacts of myrtle rust are increasing over time. Therefore, need for fungicide protection differs between species and our understanding of fungicide requirements is evolving as new information come to hand. The following are the most vulnerable species, which can be severely affected at any stage of growth:

- Native species:
    - Maire tawake/swamp maire (*Syzygium maire*)
    - *Lophomyrtus* spp., including ramarama (*L. bullata*), rōhutu (*L. obcordata*) and their natural hybrids (*L. bullata* x *L. obcordata*)

- Exotic species:
    - Lilly pilly (*Syzygium* australe)
    - Guava (*Psidium guajava*)

  Some *Metrosideros* spp. (including pōhutukawa) are severely affected as young plants and require fungicide protection to varying degrees. Mānuka (*Leptospermum scoparium*) is also somewhat vulnerable as small seedlings but has so far not required routine fungicide spraying in nurseries. Myrtle rust has not been reported on kānuka (*Kunzea* spp.) in the natural environment.

2. **Shoot flush** timing determines the risk of myrtle rust because only actively growing shoots can become infected. Data available on growth patterns in different myrtle species are currently insufficient to model seasonal growth as an aid to spray timing. The important information lacking for fungicide management is on the ability of different species to produce new growth flush under cool winter temperatures in different regions.

3. **Sources of infection** that allow myrtle rust to establish within a nursery include windborne spores blown in from outside, spores introduced on clothing, equipment etc., or infected plant material brought into the nursery. The last two are preventable through nursery biosecurity procedures, particularly good hygiene and prompt disposal of old stock of vulnerable myrtles. See System Protocols - NZPPI
4. **Climatic risk** of myrtle rust is higher in the upper North Island and lower in the South Island and at higher altitude. It tends to be slightly greater in western areas than eastern areas of both islands. Seasonal and regional risk that determines the overall need for fungicide spraying was modelled in this study and categorised as Very high, High, Moderate, Low, Very low and Negligible.

5. **Fungicide selection** guidelines suited to different seasonal and regional risk categories were developed as a rule-of-thumb guide for spray re-application intervals.

6. **Resistance management** recommendations were developed, as outlined above.

Recommendations

- Further refinement of the tool should incorporate different spraying thresholds for fungicides with different degrees of efficacy and other risk factors, particularly differences in vulnerability of different myrtle species to myrtle rust and nursery proximity to sources of infection.

- Further investigation is needed of the possibility that less intensive spraying than that suggested by this study may be adequate for nurseries where plants are completely disease free and myrtle rust is not present in the immediate environment.

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1 Popular summary

Risk-based fungicide management for myrtle rust in nurseries

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Myrtle rust is a serious threat to several New Zealand native species in the myrtle family (Myrtaceae), with at least three species facing possible local extinction in warmer areas of the North Island. Fungicides are available that can effectively control myrtle rust and although these cannot practically be used in natural conservation areas, there is scope to use them to protect and help save highly vulnerable species in plant nurseries, home gardens and council amenity and some revegetation plantings.

For nurseries, New Zealand Plant Producers Inc. (NZPPI), Plant & Food Research (PFR) and HortPlus Ltd are developing a system to maximise efficiency of fungicide use against myrtle rust through an online weather-risk tool. The project reported here tested the tool in two outdoor fungicide spray trials: Trial 1 over 85 days during summer 2021-22 and Trial 2 over 83 days during autumn 2022. The trials compared disease control under either risk-based spray timing, using the weather-risk tool, or 14-day calendar spray timing. The trial also compared disease control efficacy between seven different fungicides currently recommended for myrtle rust control and a no-fungicide treatment.

The trial results showed that four of the seven fungicides tested, triadimenol and myclobutanil, which are in FRAC Group 3 (Fungicide Resistance Action Committee; frac-code-list-2022--final.pdf) and trifloxystrobin and pyraclostrobin in Group 11, gave excellent myrtle rust control. Another fungicide, from Group 7 (fluxapyroxad), which was tested as two different formulations, gave poor control. Two other commonly used fungicides (copper and mancozeb) also gave poor control.

Nine risk-based sprays versus six calendar sprays were applied in Trial 1 and, in Trial 2, there were four risk-based sprays versus six calendar sprays. More spays were applied in Trial 1 because predicted disease risk was greater under the warm summer conditions, whereas in Trial 2, cooling autumn temperatures resulted in less frequent risk-based sprays. Both spraying strategies gave similar disease control. It was concluded that the weather-risk tool provides a practical way for targeting sprays when they are most needed, and it should help to optimise spraying efficiency.

Risk predictions by the weather-risk tool used weather data monitored at a nearby weather station and also weather forecasts up to 14 days ahead. The weather forecast based risk predictions were found to be accurate enough for making reliable spray decisions 1–3 days ahead but further ahead than 4-6 days, they were not accurate enough for spray decision making.

Spray programme requirements for myrtle rust control in relation to climatic risk in different regions and seasons were modelled for different fungicide types, differing species vulnerability and limitations on fungicide use needed to prevent fungicide resistance. This allowed fungicide use requirements to be predicted and examples of year-long spray programmes were constructed for different regions.

This study has provided important information previously lacking for the design of responsible and efficient spray programmes against myrtle rust in Aoteaora New Zealand.

2 Introduction

Myrtle rust, caused by the fungal pathogen *Austropuccinia psidii*, was first detected in New Zealand in 2017 and is now widespread throughout the North Island and upper South Island. It only attacks vulnerable native and exotic species in the Myrtaceae (myrtle family), where it can cause severe damage in conservation and urban areas and is a biosecurity threat in plant nurseries. In nurseries, it affects about 10 native and exotic species and plants must be completely free of infection to prevent the disease spreading in the wider environment. Nursery production of some native myrtles has declined partly because control procedures for myrtle rust are inadequately understood for the New Zealand situation.

Myrtle rust originated in a warmer climate than New Zealand's; it poses the greatest threat in our warmer northern areas; and the risk is increasing with climate warming. It only attacks actively growing shoots (leaves, stems, flowers and fruit) and therefore seasonal disease development is strongly influenced by the timing of growth flushes (Beresford et al. 2021). Vulnerable species grown in nurseries (Appendix 1) are generally at high risk from myrtle rust because of the large amount of active young growth that is encouraged.

Many nurseries rely on fungicide chemicals for myrtle rust control, although some are philosophically opposed to this approach. Non-chemical risk reduction strategies do exist, such as management of daily irrigation timing, increased spacing of plants to reduce disease spread and controlled irrigation and fertiliser use to manage plant growth. However, the effectiveness and practicality of those methods have not been evaluated.

There are currently no fungicide products registered specifically for myrtle rust control in New Zealand and therefore any use of fungicides comes under the conditions of 'off-label use' See Off-Label use of Agrichemicals-NZGAP Guideline for Growers v1.5 (Dec 2021).pdf for explanation of the rules that must be followed for off label use. The application rate for fungicide products used for myrtle rust should be chosen from the label rate for an appropriate equivalent crop: Ministry for Primary Industries - ACVM Register (nzfsa.govt.nz).

A Growsafe Approved Handler Certificate is generally required when purchasing and applying fungicides. Growsafe information can be found at: Home (growsafe.co.nz). Anyone can buy fungicides from garden supply shops without an Approved Handler Certificate, but Growsafe Basic training is still recommended. Some fungicide products available at garden supply shops contain active ingredients that are effective against myrtle rust.

Most fungicides potentially affect human health and the environment. For the hazard classification system for fungicides see Risks of Agrichemicals (growsafe.co.nz). To find out about the hazards for individual products, search online for the safety data sheet (SDS) under the fungicide product name.

Nursery use of fungicides currently relies on calendar-based spraying with a typical re-application interval of 7–14 days if myrtle rust risk is perceived to be high and up to 21 days or longer when risk is perceived to be low. This approach may lead to 20–30 fungicide applications over a year and some of these sprays may be unnecessary if they are applied during periods of low disease risk. We know that disease risk varies daily and seasonally according to weather conditions and geographically with regional climate (Beresford et al. 2018; Appendix 2). However, there is currently no guidance for nursery managers on how to adjust fungicide spraying to match disease risk at particular times of the year or in different areas of New Zealand.

Several modern synthetic fungicides give highly effective control of myrtle rust in vulnerable native species, including *Lophomyrtus* spp. (ramarama and rōhutu) and *Metrosideros excelsa* (pōhutukawa) (Pathan et al. 2020). A summary of which myrtle species need fungicide protection is provided in Appendix 1. The most effective fungicide active ingredients are in the demethylation inhibitor (DMI; triazole) and quinone outside inhibitor (QoI; strobilurin) fungicide groups, although different compounds and product formulations within those groups may vary in their effectiveness. Another group widely used in crop protection is the succinate dehydrogenase inhibitor (SDHI) group but few of these active ingredients have been tested on myrtle rust. Older ‘broad-spectrum’ fungicides, such as copper, mancozeb and chlorothalonil, can also be used, although they are reported to be less effective. Appendix 3 provides a glossary of fungicide-related terms.

Some fungicides are at risk from the development of fungicide resistance in plant pathogens. These have a mode of action that inhibits a single biochemical pathway in the pathogen’s metabolism (single-site inhibitors). They are often highly effective at controlling the target pathogen with minimal effects on non-target organisms. By contrast, many older fungicides are more general poisons that inhibit multiple biochemical pathways. These are called multi-site inhibitors or broad-spectrum fungicides and are not at risk from resistance (Appendix 3). They include copper compounds and the older synthetic fungicides and tend to require higher doses to be effective and often have greater adverse environmental impacts than single-site inhibitors.

The large number of sprays required in nurseries risks selecting fungicide resistance in the pathogen. Modern synthetic fungicides that are at risk from resistance, rather than the broad-spectrum fungicides. There is currently no resistance management strategy to guide how fungicides should be deployed for myrtle rust control in New Zealand.

A predictive online weather-risk tool is currently being developed by The New Zealand Institute for Plant and Food Research Limited (PFR), HortPlus Ltd and New Zealand Plant Producers Incorporated (NZPPI) to help nursery managers rationalise fungicide use. It is implemented on the ‘NZPPI Plant Disease Management Platform’ as the ‘Myrtle Rust Cumulative Risk’ tool and it identifies periods when seasonal myrtle rust risk is high so that fungicides can be targeted to when they are most needed (NZPPI Plant Disease Management Platform | Myrtle Rust Cumulative Risk (metwatch.nz)). This tool aims to achieve disease control with more efficient use of fungicides and at the same time reduce the risk of fungicide resistance.

This project, funded by the Ministry for Primary Industries (MPI) aimed to investigate control of myrtle rust in a nursery situation under the following three objectives:

1. Compare risk-based and calendar spraying strategies using single-site and multi-site mode of action fungicides.
2. Develop a weather-risk tool for spray management using the PFR/HortPlus climatic risk tool being developed for NZPPI to decide optimal spray timing.
3. Develop fungicide resistance prevention guidelines in conjunction with NZPPI.

During the field fungicide trials to address Objective 1 and develop the weather-risk tool for Objective 2, it became clear other considerations affecting myrtle rust fungicide programmes also needed to be addressed. These were: myrtle species vulnerability, seasonal growth flush, sources of infection, regional and seasonal variation in climatic risk and the required application frequency of different fungicide types. To address these an additional objective is included in this report:

4. Develop recommendations on risk factors that affect the design of myrtle rust spray programmes in New Zealand nurseries.

3 Spray trials (Objectives 1 and 2)

3.1 Spray trial materials and methods

Two outdoor trials on fungicide control of myrtle rust in plants exposed to natural infection from airborne *A. psidii* spores were conducted at PFR's Pukekohe Research Station during summer and autumn 2021–22. Potted plants of the vulnerable myrtle rust host *Lophomyrtus* sp. 'Red Dragon' were used. This is a horticultural selection of a natural *L. bullata* x *L. obcordata* hybrid and was clonally propagated from cuttings at PFR Ruakura in 10-cm pots using commercial potting mix (Figure 1). The two trials were run over the following dates:

- Trial 1, 85 days from 7 December 2021 to 1 March 2022.
- Trial 2, 83 days from 2 March to 22 May 2022.

Figure 1. Potted *Lophomyrtus* plants (left) and myrtle rust symptoms (right) in Trial 1 at Pukekohe Research Station.

3.1.1 Fungicide treatments, spray timing and trial design

Each trial was laid out in a randomised complete block design with six replicate blocks and four (Trial 1) or five (Trial 2) fungicide treatments plus a no-fungicide control sprayed with water (Table 1). Each treatment in each replicate block used a single potted plant with 30–50 actively growing shoots at the start of each trial. All sprays were applied by hand-held pressure sprayer with spray drift between plants avoided by grouping treatments away from the trial during spraying then returning pots to their randomised positions.

Two spray timing treatments were used in both trials, as follows:

1. Calendar spraying, with the first spray applied at the start of each trial then applications repeated fortnightly.
2. Risk-based spraying, with the first spray applied at the start of each trial then subsequent sprays timed according to the online weather-risk tool (Myrtle Rust Cumulative Risk part of the NZPPI Plant Disease Management Platform), as implemented by HortPlus Ltd (NZPPI Plant Disease Management Platform | Myrtle Rust Cumulative Risk (metwatch.nz))

At each calendar or risk-based spray date, every fungicide treatment was applied, so there were no differences in re-application intervals for different fungicide products.

Table 1. Fungicide products, active ingredients and spray timing treatments used in Trial 1 and Trial 2.

Treat-ment #	Spray timing treatments	Fungicide products	[1]Product formul-ation	Active ingredient	Product application rate (mL or g/L)	Active ingredient application rate (mL or g/L)
Trial 1 (7 Dec 2021 – 1 Mar 2022)						
1	Calendar	Vandia®	EC	Triadimenol	1.00	0.25
2	Calendar	Flint®	WDG	Trifloxystrobin	0.10	0.05
3	Calendar	Sercadis®	SC	Fluxapyroxad	0.20	0.06
4	Calendar	Kocide® Opti™	WDG	Copper hydroxide	1.00	0.30
5	Risk-based	Vandia®	EC	Triadimenol	1.00	0.25
6	Risk-based	Flint®	WDG	Trifloxystrobin	0.10	0.05
7	Risk-based	Sercadis®	SC	Fluxapyroxad	0.20	0.06
8	Risk-based	Kocide® Opti™	WDG	Copper hydroxide	1.00	0.30
9	Nil-fungicide	–	–	Water		
Trial 2 (2 Mar – 22 May 2022)						
1	Calendar	Vandia®	EC	Triadimenol	1.00	0.25
2	Calendar	Validus®	EW	Myclobutanil	1.00	0.20
3	Calendar	Comet®	EC	Pyraclostrobin	0.50	0.13
4	Calendar	Imtrex®	EC	Fluxapyroxad	2.00	0.13
5	Calendar	Mancozeb	WDG	Mancozeb	2.10	1.58
6	Risk-based	Vandia®	EC	Triadimenol	1.00	0.25
7	Risk-based	Validus®	EW	Myclobutanil	1.00	0.20
8	Risk-based	Comet®	EC	Pyraclostrobin	0.50	0.13
9	Risk-based	Imtrex®	EC	Fluxapyroxad	2.00	0.13
10	Risk-based	Mancozeb	WDG	Mancozeb	2.10	1.58
11	Nil-fungicide	–	–	Water		

[1] EC = emulsifiable concentrate; WDG = water dispersible granule; SC = suspension concentrate; EW = oil in water emulsion.

Choice of fungicide products for the trials

In Trial 1, Vandia® contains the Group 3 DMI fungicide triadimenol, which has been widely shown to be highly effective against myrtle rust, with good curative (systemic) and protectant activity. Flint® contains the Group 11 QoI fungicide trifloxystrobin, which has also been found to be highly effective with protectant and curative activity. Sercadis® contains the Group 7 SDHI fungicide fluxapyroxad and the efficacy of SDHIs against myrtle rust has not been widely evaluated. They have protectant activity and limited curative activity. Kocide® Opti™ contains copper hydroxide, which is one of the copper salts widely used in broad-spectrum copper fungicides.

In Trial 2, Vandia was used again to provide a comparison between the two trials. Validus® contains myclobutanil, another DMI fungicide, and is available to the public from garden shops in the product Yates Fungus Fighter. Comet® contains pyraclostrobin, which is an alternative QoI fungicide to trifloxystrobin. Imtrex® is an alternative formulation of fluxapyroxad (Sercadis in Trial 1) and was used at a higher active ingredient rate than Sercadis was. Mancozeb is a broad-spectrum protectant fungicide with some activity against myrtle rust.

Fungicide products have different formulations with various chemicals added to achieve effective delivery of the active ingredient to the plant. Trial 2 focused on EC formulations, which may improve fungicide adsorbtion onto plant surfaces, or uptake of systemic fungicides into plants, compared with suspension concentrate (SC) or water dispersible granule (WDG) formulations.

3.1.2 Use of the weather-risk tool

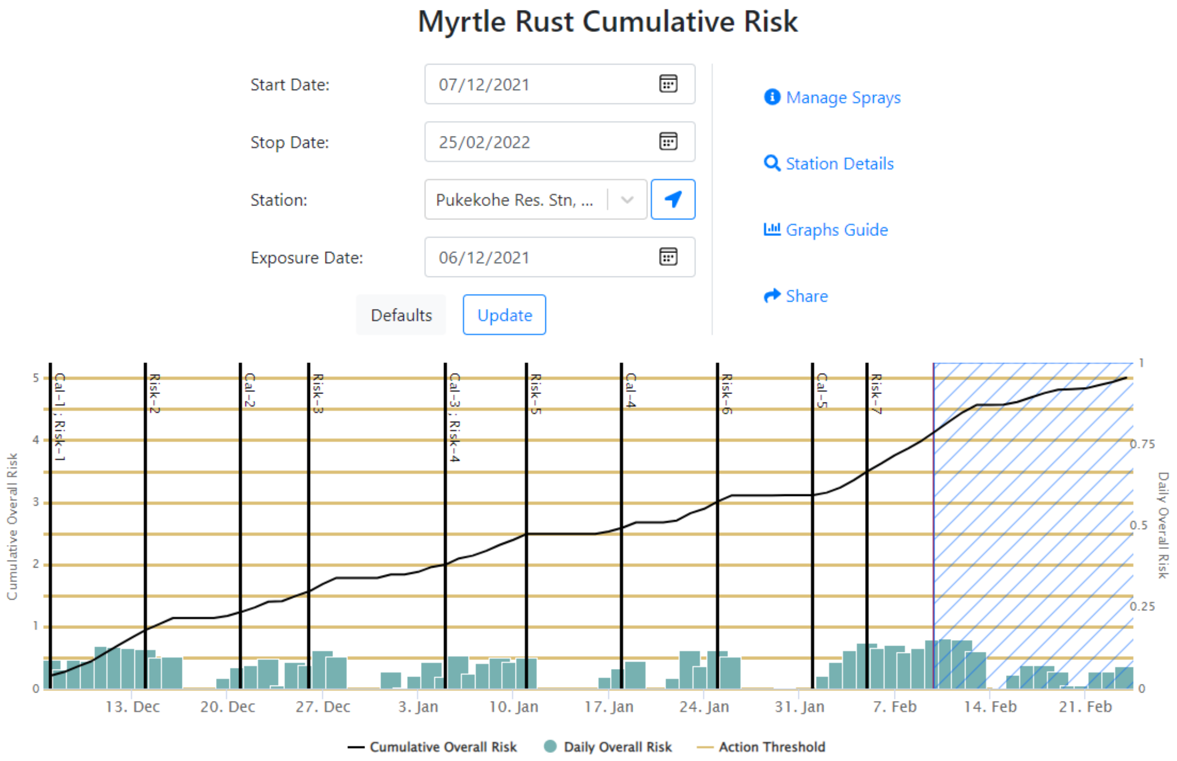
The weather-risk tool calculates risk indices from monitored and forecast weather data, with weather forecasts provided by IBM. The risk indices are as follows:

1. **Daily infection risk** (values 0–1) by spores deposited on vulnerable plants calculated from temperature, duration of high relative humidity (>85%) and solar radiation (Beresford et al. 2018).
2. **Daily latent development rate** is the rate of fungal growth inside the plant between infection and the production of new spores, as determined by daily mean air temperature (Beresford et al. 2020).
3. **Daily overall risk** is the product of 1) and 2) above. This index was accumulated daily as the **cumulative overall risk**, which was used for spray timing. Thresholds of cumulative overall risk were set at increments of 0.5 risk units and when the value passed each threshold a risk-based spray was applied. Thus, the risk-based sprays were applied more frequently when myrtle rust risk was higher, e.g., during warm humid periods.

Daily variation in overall risk values within a season is largely determined by the infection risk component, whereas seasonal and geographic variation are influenced more by the latent development rate component, which becomes very slow at cool temperatures (<10–12°C).

Figure 2 shows an example weather-risk display during Trial 1. User settings were input as follows:

- **Station**, i.e., a nearby weather station of interest in the HortPlus/PFR network, in this case ‘Pukekohe Research Station’.
- **Exposure Date** when nursery plants were first exposed to airborne myrtle rust spores and when risk accumulation starts.
- **Start Date** and **Stop Date** for the viewing window of the risk display.
- **Manage Sprays** for user entry of the spray dates that appear on the risk display.



Myrtle Rust Cumulative Risk

Start Date: 07/12/2021

Stop Date: 25/02/2022

Station: Pukekohe Res. Stn, ...

Exposure Date: 06/12/2021

Figure 2. Example risk display of the myrtle rust online weather-risk tool implemented by HortPlus Ltd for Trial 1 on 9 February 2021. User settings are at the top and the graph shows cumulative risk (black line), 14-day weather forecast component (hatched area to the right), daily overall infection risk (bars) and spray dates (vertical black lines).

For Trial 1, the Exposure Date was 6 December 2021. Calendar sprays were applied fortnightly and risk-based sprays were applied each time cumulative risk passed spray thresholds at increments of 0.5 cumulative risk units (i.e., 0.5, 1, 1.5, etc.).

For Trial 2, the Exposure Date was 1 March 2022. Calendar sprays were applied fortnightly and risk-based sprays were applied each time cumulative risk passed spray thresholds at 0.75 cumulative risk unit increments (i.e., 0.75, 1.5, 2.25, etc.).

3.1.3 Disease and growth flush assessments

Disease and plant growth were assessed in both trials at the time when myrtle rust effects on the plants were at their peak. The following variables were recorded:

- **Disease severity:** Percentage of shoots per plant with active myrtle rust symptoms, including yellow spore pustules on leaves and/or stems and/or shoot tip dieback.
- **New flush:** Percentage of shoots per plant with new leaves and stems actively emerging.

In Trial 1, assessments were made on three dates, 6 January, 26 January, and 8 March 2022. Trial 2 was assessed on 20 April 2022 (Table 2).

3.1.4 Data analysis

Statistical analysis of the disease severity and new flush data was done using fixed effects ANOVA in Genstat 19th edition. For each trial, mean separation for the fungicide product effect (including the unsprayed control) was by the Bonferroni method (Hsu 1996). The factorial effect of spray timing by fungicide product (excluding the unsprayed control) was analysed by two-way ANOVA. Effects are presented graphically in the text, with significant fungicide product differences indicated by letters and a significant fungicide product by spray timing interaction indicated by asterisks. (The fungicide timing effect was not significant in either trial.)

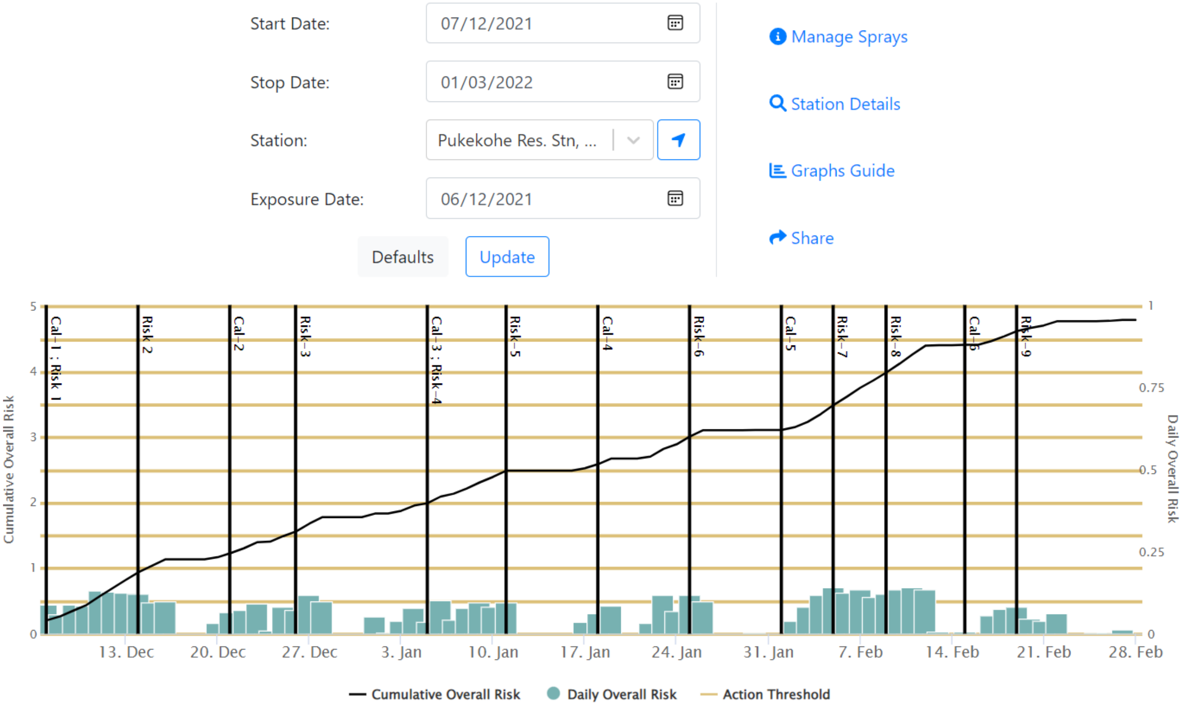
3.2 Spray trial results

3.2.1 Trial 1

Myrtle rust became evident in Trial 1 within 3 weeks of trial set up, although symptoms were initially sparse. The plants had been held outside at Pukekohe and were already infected at the start of the trial. The early appearance of rust generated high disease pressure and provided a good test of the different fungicide products and the calendar versus risk-based spraying strategies.

Trial 1 Calendar and risk-based spraying frequency

Trial 1 received six fortnightly calendar sprays and nine risk-based sprays applied according to spray thresholds at 0.5 cumulative overall risk unit increments (Figure 3 and Table 2).



Start Date: 07/12/2021
Stop Date: 01/03/2022
Station: Pukekohe Res. Stn, ...
Exposure Date: 06/12/2021

Figure 3. Trial 1: Daily overall risk (bars), Cumulative overall risk (thin black line) and spray dates (vertical black lines) for the calendar (Cal-) and risk-based (Risk-) spray regimes. Calendar sprays were applied fortnightly and risk-based sprays were applied each time the cumulative risk line passed one of the horizontal yellow spray threshold lines, which were at increments of 0.5 cumulative overall risk units.

Table 2. Spray application dates, intervals between dates and disease assessment dates in Trial 1 and Trial 2.

Application #	Calendar spray dates	Spray interval (days)	Risk-based spray dates	Spray interval (days)	Disease assessment dates
Trial 1: start 7 Dec 2021; end 1 Mar 2022 (85 days)					
1	7-Dec-21		7-Dec-21		6-Jan-22
2	21-Dec-21	14	14-Dec-21	7	26-Jan-22
3	4-Jan-22	14	26-Dec-21	12	8-Mar-22
4	18-Jan-22	14	5-Jan-22	10	
5	1-Feb-22	14	11-Jan-22	6	
6	15-Feb-22	14	25-Jan-22	14	
7			5-Feb-22	11	
8			9-Feb-22	4	
9			19-Feb-22	10	
Total/mean	6	14.0	9	9.25	3
Trial 2: start 2 Mar 2022; end 22 May 2022 (82 days)					
1	2-Mar-22		2-Mar-22		20-Apr-22
2	16-Mar-22	14	24-Mar-22	22	
3	30-Mar-22	14	13-Apr-22	20	
4	13-Apr-22	14	16-May-22	33	
5	27-Apr-22	14			
6	11-May-22	14			
Total/mean	6	14.0	4	25.0	1

Trial 1 Fungicide product efficacy

Effects on disease severity

At all three disease assessment dates there was a significant fungicide treatment effect ($p < 0.001$) for differences in mean myrtle rust severity between fungicide products (Figure 4). On 6 January and 26 January 2022, Vandia gave very high degree disease control and was significantly better than Flint, which in turn was significantly better than Kocide Opti, Sercadis and the Nil-fungicide control, with the last three not significantly different from each other.

On 8 March, disease severity had decreased markedly in all plots. For the more effective treatments (Vandia and Flint), this was because myrtle rust had been effectively suppressed. For the less effective treatments (Sercadis, Kocide Opti and Nil-fungicide control), it was because myrtle rust damage early in the trial had killed shoots and although regrowth was occurring slowly, the new shoots had not yet become infected. Flint was performing relatively better on 8 March than in the previous two assessments and was not significantly different from Vandia. This was probably because Flint, which has strong protectant activity, as opposed to the strong curative activity of Vandia, had been relatively more effective later in the trial at preventing new infection.

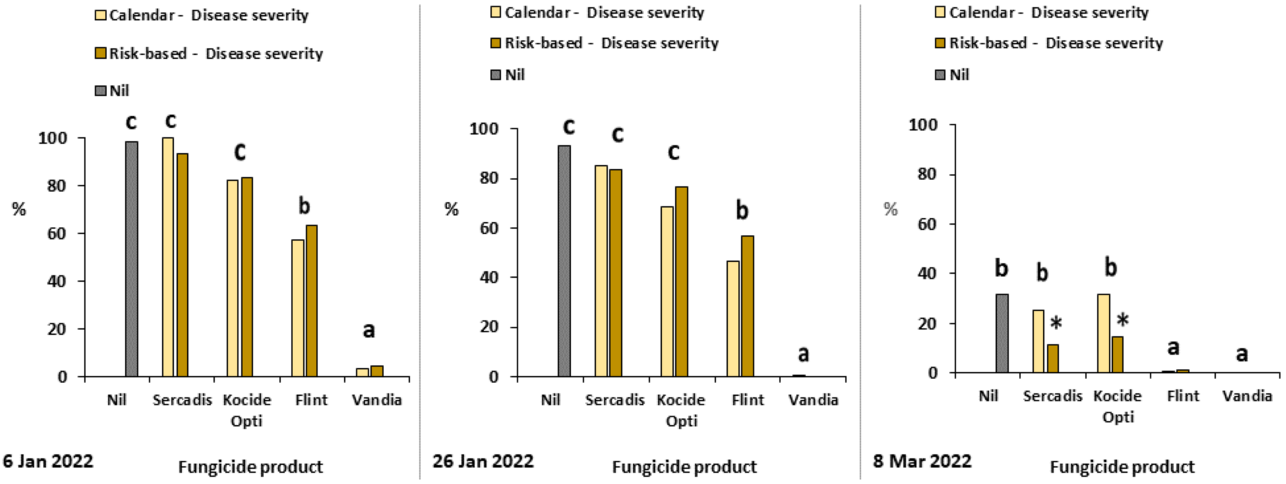


Figure 4. Trial 1: Effects of fungicide product (four fungicides and nil-fungicide control) and spray timing (calendar or risk-based) on myrtle rust severity (percentage of shoots per plant infected) on three dates. For the fungicide product effect, bars accompanied by the same letter are not significantly different (α = 0.05; Bonferroni test). The timing strategy effect was not significant (*p* > 0.2) but on 8 March, the fungicide product x fungicide timing interaction was significant (*p* = 0.048), as indicated by asterisks.

Effects on growth flush

The differences in new growth flush were essentially the inverse of the disease severity differences and the Vandia-treated plants had the greatest growth flush on 6 and 26 January followed by Flint (Figure 5). However, towards the end of the trial (8 March), Flint was not significantly different from Vandia, as was the case for disease severity. On 8 March, new flush for the less effective fungicide treatments (Sercadis, Kocide Opti and Nil-fungicide control) was relatively greater than it had been earlier in the trial. This appeared to be because, after the first wave of infection that killed all new growth in these treatments, new shoots that emerged during February and early March had not been affected by re-infection by the end of the trial.

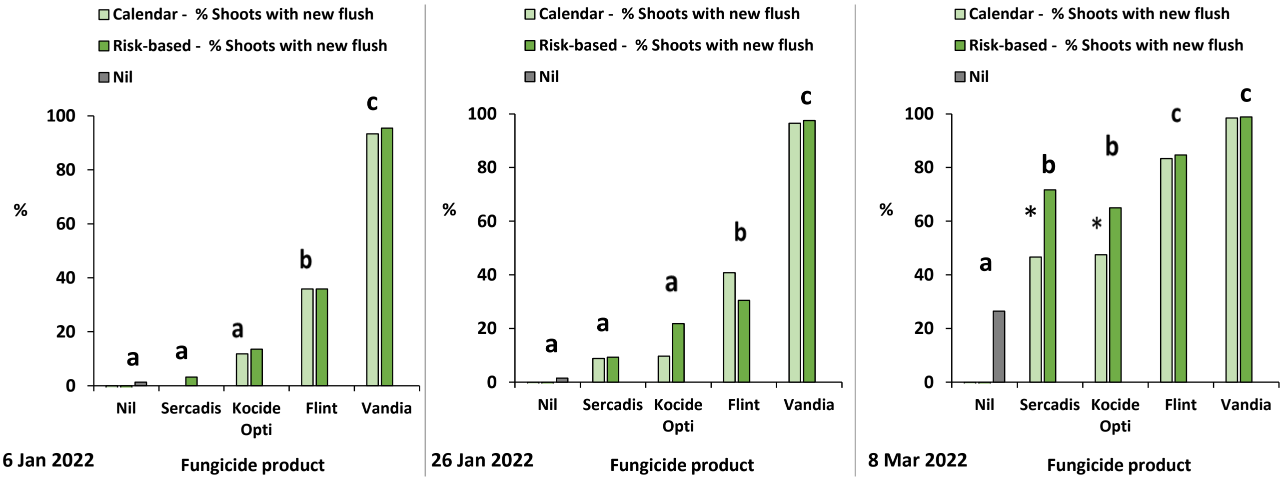


Figure 5. Trial 1: Effects of fungicide product (four fungicides and a nil-fungicide control) and spray timing (calendar or risk-based) on percentage of shoots with new growth flush on three dates. For the fungicide product effect, bars accompanied by the same letter are not significantly different (α = 0.05; Bonferroni test). The timing strategy effect was not significant (*p* > 0.5) except on 8 March (*p* = 0.003) when the fungicide product x fungicide timing interaction was also significant (*p* = 0.039), as indicated by asterisks.

Trial 1 Calendar versus risk-based spraying

Despite fewer sprays under the calendar regime (six as opposed to nine for risk-based timing), the differences in disease severity and growth flush between the two spray regimes were generally small and not statistically significant. However, towards the end of the trial (8 March) the fungicide product x timing strategy interaction was significant, with better disease control (lower disease severity and greater growth flush) for risk-based spraying of the less effective fungicides (Sercadis and Kocide Opti), as shown in Figure 4 and Figure 5. This indicates that the lower efficacy of these two fungicides was helped by either better spray timing or more spray applications in the risk-based regime, or both.

Trial 1 Fungicide effects on plant growth

Internode shortening was noted in the plants treated with Vandia (Figure 6), which gave these plants a rather attractive compact growth form. It is known that some triazole fungicides, including triadimenol, can have growth regulating effects (Fletcher et al. 1986). QoIs and SDHIs can sometimes produce plant growth promoting effects (Bartlett et al. 2002) but these were not observed in this study. No plant damage from fungicide phytotoxicity was observed in Trial 1.

Figure 6. Shortened internodes in a Vandia-treated plant (left) compared with a nil-fungicide control plant (right). Although the nil-fungicide plant has myrtle rust damage, the stem length between leaf nodes is clearly longer than in the Vandia-treated plant.

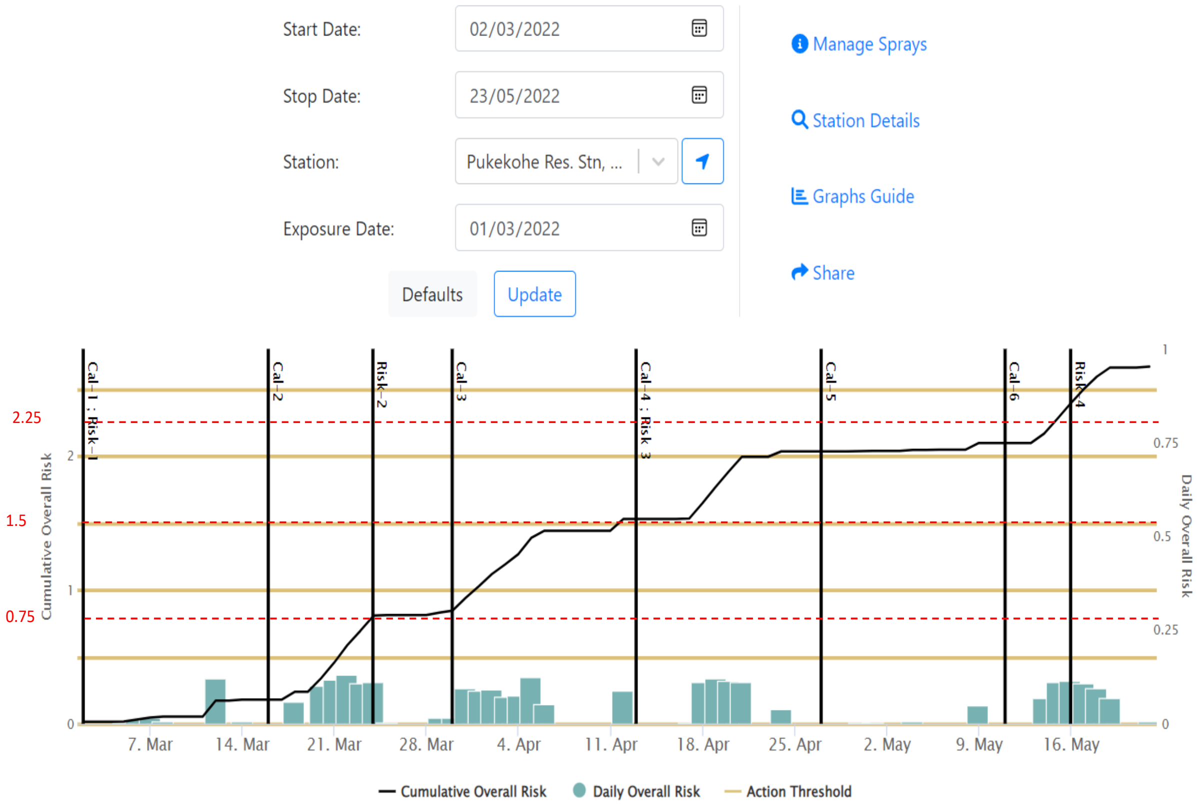
3.2.2 Trial 2

Trial 2 was conducted during autumn to determine how the risk-based spraying frequency was affected by cooling autumn temperatures. In autumn, infection conditions are less often favourable and plant growth is slower, meaning that the number of shoots vulnerable to myrtle rust declines. The risk-based spray re-application threshold increment was increased to 0.75 overall risk units to help generate fewer fungicide applications in the risk-based regime compared with the 14-day calendar regime.

The plants used in Trial 2 were already infected when the trial was set up on 1 March 2022 with active spore production visible and some shoot dieback present. This ensured that rust was present in the trial, but it was unfortunately not uniform across all the plants, so it added to variability within the trial.

Trial 2 Calendar and risk-based spraying frequency

Trial 2 received six 14-day calendar sprays and four risk-based sprays applied according to the 0.75 increment spray thresholds (Figure 7 and Table 2).



Start Date: 02/03/2022

Stop Date: 23/05/2022

Station: Pukekohe Res. Stn, ...

Exposure Date: 01/03/2022

Figure 7. Trial 2: Myrtle rust daily overall risk (bars), cumulative overall risk (thin black line) and spray dates (vertical black lines) for the calendar (Cal-) and risk-based (Risk-) spray regimes. Calendar sprays were applied fortnightly and risk-based sprays were applied each time the cumulative risk line passed one of the red horizontal lines at increments of 0.75 cumulative overall risk units (numbers in red on the Y-axis).

Trial 2 Fungicide product efficacy

Effects on disease severity

At the 20 April assessment, disease severity was suppressed significantly more ($p < 0.01$) in the Vandia, Validus and Comet treatments compared with Imtrex, Mancozeb and Nil-fungicide (Figure 8). Although Vandia, Validus and Comet were not significantly different from each other, there was a trend for mean disease severity to rank Vandia > Validus > Comet. Disease severity was very high (70–90%) in the Nil-fungicide control, Imtrex and Mancozeb treatments, which were not significantly different from each other ($p > 0.1$). For these treatments there was a trend for mean disease severity to rank Nil-fungicide > Mancozeb > Imtrex.

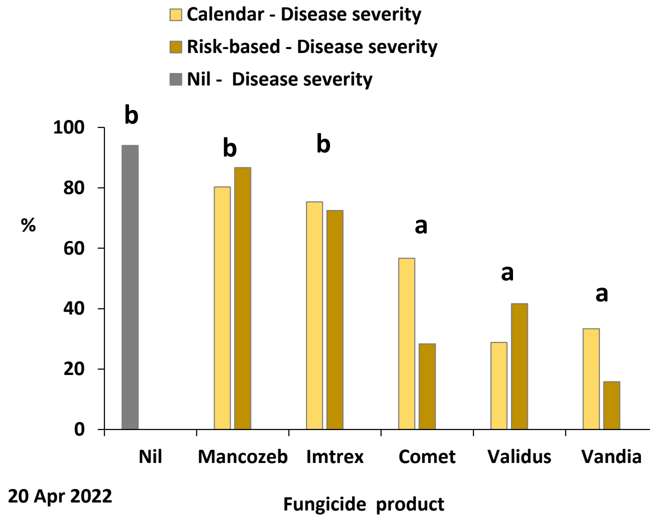


Figure 8. Trial 2: Effects of six fungicide product treatments, including nil-fungicide control, and fungicide timing strategy (calendar or risk-based) on percentage of shoots infected by myrtle rust on 20 April 2022. For the fungicide product effect, bars accompanied by the same letter are not significantly different (α = 0.05; Bonferroni test). The timing strategy effect was not significant ($p > 0.9$) and the fungicide product x fungicide timing interaction was not significant ($p > 0.5$).

Effects on growth flush

As in Trial 1, differences in new growth flush between treatments were essentially the inverse of disease severity (Figure 9). Although Comet, Validus and Vandia were not significantly different ($p > 0.05$), Validus had a slightly greater percentage of shoots with new growth flush than Vandia. Again, the Imtrex, Mancozeb and Nil-fungicide treatments were not significantly different from each other.

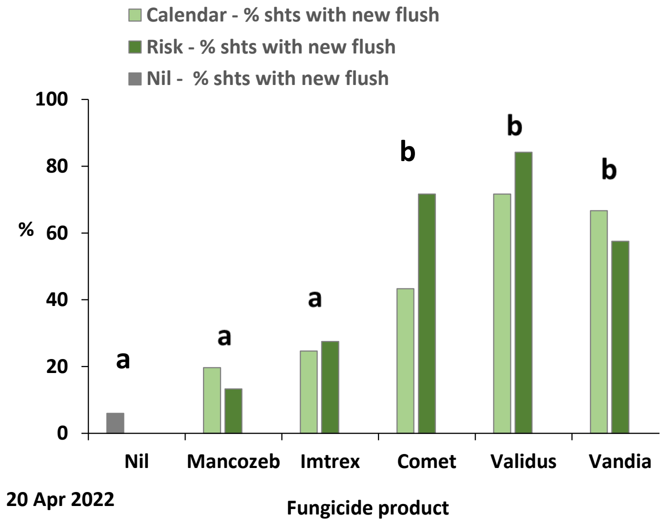


Figure 9. Trial 2: Effects of five fungicide product treatments plus nil-fungicide control and fungicide timing strategy (calendar or risk-based) on percentage of shoots with new growth flush on 20 April 2022. The fungicide product effect was significant ($p < 0.001$) and bars accompanied by the same letter are not significantly different (α = 0.05; Bonferroni test). The timing strategy effect was not significant ($p > 0.2$) and the fungicide product x fungicide timing interaction was not significant ($p > 0.5$).

Trial 2 Effect of calendar versus risk-based spraying

The spray timing effect in Trial 2 was not significant and neither was the fungicide product x spray timing interaction. However, looking at Figure 8, there was a suggestion that, for Validus, disease severity with risk-based timing was relatively greater (less disease control) than for Comet or Vandia. This could indicate that, with the longer spray intervals in the risk-based regime, Validus was less effective, possibly because myclobutanil has relatively poor protectant activity. This is known to occur in apples for *Venturia inaequalis* (black spot) control. It would suggest that mixing Validus, or any other myclobutanil product, with an effective broad-spectrum protectant fungicide would be beneficial.

Trial 2 Fungicide effects on plant growth

The internode shortening in the plants treated with Vandia noted in the first trial (Figure 6) was also evident in the second trial. No other growth-regulating effect or phytotoxicity from the fungicide treatments was observed in Trial 2.

3.3 Spray trial discussion

The two DMI fungicides used in these trials, Vandia (triadimenol; Trial 1) and Validus (myclobutanil; Trial 2), were highly effective at controlling myrtle rust even under high disease pressure.

The QoI fungicides Flint (trifloxystrobin; Trial 1) and Comet (pyraclostrobin; Trial 2) were also very effective, especially Comet. In Trial 1, Flint was significantly less effective than Vandia, whereas in Trial 2, Comet was not significantly different from Vandia and Validus. Comet was used at 2.6 times the active ingredient rate that trifloxystrobin had been used at in Trial 1, which may account for its relatively better performance.

The SDHI fungicide fluxapyroxad, used as an SC formulation (Sercadis) in Trial 1 and an EC formulation (Imtrex) in Trial 2, did not perform very well in either trial and was similar to the broad-spectrum fungicides. It only performed better than the Nil-fungicide control towards the end of Trial 1 when it gave significant protection of new leaf flush. Mancozeb was also only significantly better than the Nil-fungicide control at that time.

Imtrex was used in Trial 2 at twice the application rate of the active ingredient (fluxapyroxad) than Sercadis in Trial 1, but this did not give an improvement in relative performance. These results raise the question of whether fluxapyroxad is effective, indeed, whether SDHIs in general are effective against myrtle rust.

The two broad-spectrum fungicides used in the trials, copper and mancozeb, gave only weak control of myrtle rust. Broad-spectrum protectant chemicals such as these, and chlorothalonil, which is also recommended (Appendix 3), probably give protection against infection under low-risk conditions but will require a relatively short re-application interval, e.g., 7 days when risk is high.

There were few differences in myrtle rust control between the calendar and risk-based spray timing treatments. The only statistically significant effect was towards the end of Trial 1 when use of the less effective products (Sercadis and Kocide Opti) was relatively more effective when they were applied according to the risk-based regime than the fortnightly calendar regime. This could have been due to better timing of applications or the greater number of applications in the risk-based regime, or both. In Trial 2, there was no significant difference in disease severity or amount of growth flush between the risk-based regime, with four sprays, and the Calendar regime, with six sprays, suggesting that the smaller number of sprays timed according to risk was as effective as the 14-day calendar spray timing.

Where risk-based spraying will make an important difference to spray decision making is in determining appropriate spray re-application intervals in different seasons, particularly during low-risk periods in autumn, winter, and spring.

Variability of disease severity within these trials was very high, which may have limited the ability to detect fungicide treatment differences. In future trials, a greater number of treatment replicates should be used to reduce this problem.

3.4 Further fungicide testing

Although the broad-spectrum fungicides recommended for myrtle rust control have low efficacy compared with the DMI and QoI fungicides, they are important in myrtle rust spray programmes as mixing and alternation partners for fungicide resistance management (see below). Other broad-spectrum fungicides that could be tested are folpet (e.g., Folpan® 800 WG), which provides protection against rust diseases in cereal crops, as well as other copper formulations, including copper oxychloride and copper oxide, which may be more persistent in rainy conditions.

Other DMI and QoI fungicide active ingredients than those used in these spray trials are also recommended for myrtle rust (Appendix 3). These are likely to be effective but individual products will vary in their protectant and curative activity so specific testing of these should be carried out. Other SDHI fungicides also need to be tested, particularly benzovindiflupyr (Elatus Plus®), which is recommended by NZPPI for myrtle rust.

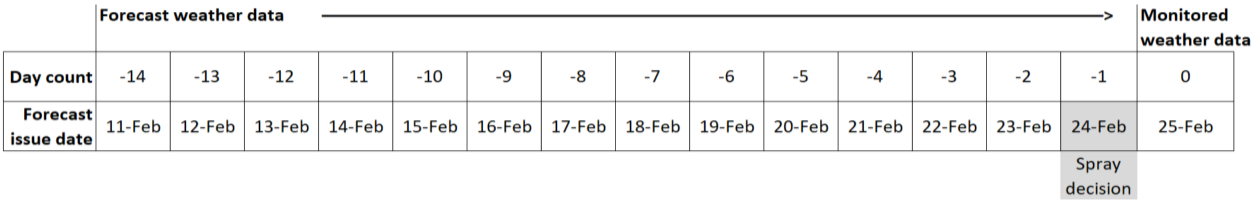
Bio-fungicides, including biological control agents and plant defence elicitors, are currently being researched by PFR in the Beyond Myrtle Rust MBIE programme. A natural product, Timorex Gold, which is a tea tree extract form *Melaleuca alternifolia*, has been previously tested but was found to be ineffective against myrtle rust (Adusei-Fosu & Rolando 2019).

4 Accuracy of weather forecast risk predictions

4.1 Forecast-based risk analysis methods

If the online weather-risk tool was used with only monitored weather data, then the earliest a risk-based spray could be applied (Day 0; Figure 10) would be the day after a cumulative overall risk threshold was passed (Day −1) because the actual monitored risk can only be known at the end of that day. Therefore, if only monitored weather data were available, every risk-based spray would be at least one day late.

The weather-risk tool provides weather forecast data from IBM to predict future risk for the unfinished part of Day −1 and a further 13 days ahead (Days −1 to −14). This provides the potential for a spray decision to be made well in advance of when the spray is needed. However, it needs to be determined which, if any, of the 14 days of forecasts are accurate enough to be reliably used for timing sprays.



	Forecast weather data →														**Monitored weather data**
Day count	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0
Forecast issue date	11-Feb	12-Feb	13-Feb	14-Feb	15-Feb	16-Feb	17-Feb	18-Feb	19-Feb	20-Feb	21-Feb	22-Feb	23-Feb	24-Feb	25-Feb
														Spray decision	

Figure 10. Day numbering and example dates for accuracy analysis of weather forecast–based cumulative overall risk predictions.

The accuracy of each of the 14 forecast days of cumulative overall risk was investigated in terms of the hit rate (proportion of predictions that are correct) in relation to the monitored risk on each Day 0. An allowance was made for small inaccuracies in predicted risk by accepting a forecast risk value as correct if it was within ±0.15 risk units of the monitored value. Hit rate was examined for all the sets of

14 forecast days ahead of each Day 0 between 25 December 2021 and 22 February 2022 (60 days) in Trial 1 and between 15 March and 9 May 2022 (56 days) in Trial 2.

It was considered that the hit rate must be >0.75 for a spray decision based on a given forecast day to be useful. If the hit rate was as low as 0.50, the spray decision would be no better than random chance. A spray decision based on a hit rate <0.50 would be misleading as it would be more likely to be incorrect than correct.

The forecast and monitored risk data for this analysis were obtained from the ‘Export Event Summary’ within the ‘Myrtle Rust Cumulative Risk’ tool. This information was sent to PFR by HortPlus Ltd in an automated email each day at 0800 h New Zealand Daylight Time (NZDT) or at 0700 h New Zealand Standard Time (NZST) after 3 April 2022. This time of day was chosen so that a spray decision could be made in the morning and spraying of the weather-risk treatments in Trial 1 or Trial 2 could be done that day.

4.2 Forecast-based risk analysis results

The accuracy analysis showed that the hit rate decreased as the number of days ahead of Day 0 increased (Figure 11). In Trial 1, the hit rate was a perfect 1.00 on Day −1 and 0.82 on Day −2, so these two forecast days with hit rates >0.75 were useful for making spray decisions. However, on Day −3, the hit rate was only 0.68 and from Day −5 and further ahead, it was no better than random chance (≤0.50).

Trial 2 was slightly better, with accuracy acceptable for spray decision making on Days −1 (1.00) and −2 (0.96) and still possibly acceptable on Day −3 (0.75). Accuracy was no better than random chance on Day −7 and further ahead than that (≤0.50).

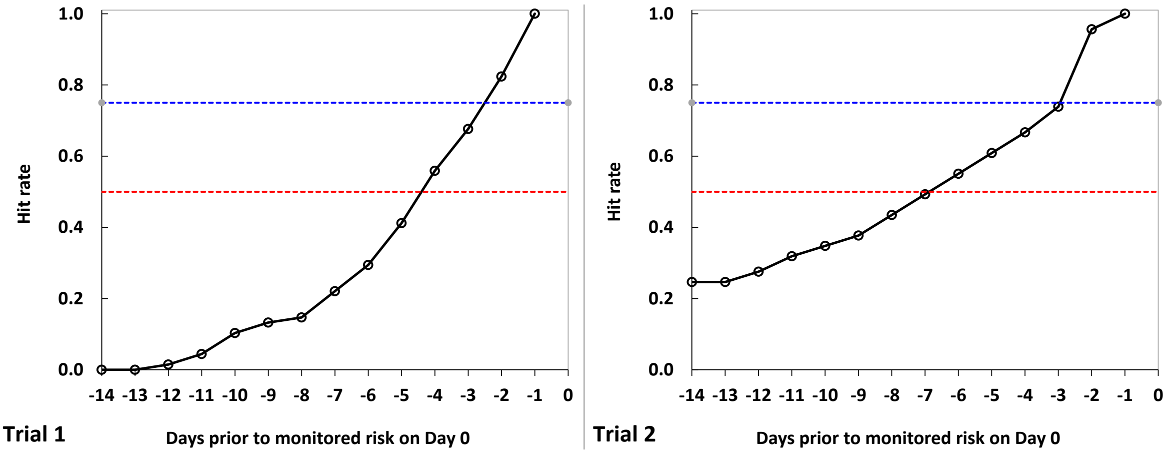


Figure 11. Accuracy of weather forecast–based predictions of cumulative overall risk in terms of the hit rate (proportion of correct predictions) compared with monitored cumulative overall risk on Day 0 for 14 days of forecasts (Day −14 to Day −1). The analysis was conducted, for Trial 1, over 68 days (25 Dec 2021 – 2 Mar 2022) and, for Trial 2, over 69 days (15 Mar – 22 May 2022). A hit rate ≥0.75 (top blue dashed line) is considered adequate for spray decision making, a hit rate of 0.5 (bottom red dashed line) is no better than random chance and a hit rate < 0.5 is misleading.

It was found that forecast accuracy tended to be greater during periods of low infection risk (fine weather) than periods of high infection risk (humid, rainy weather). This appeared to be related to poor prediction of exactly when weather systems with northerly wind flows bringing high relative humidity and possibly rain would arrive. Figure 12 shows, for predictions of daily infection risk over all 14 forecast days, the tendency for the hit rate to decrease as the monitored daily infection risk increases.

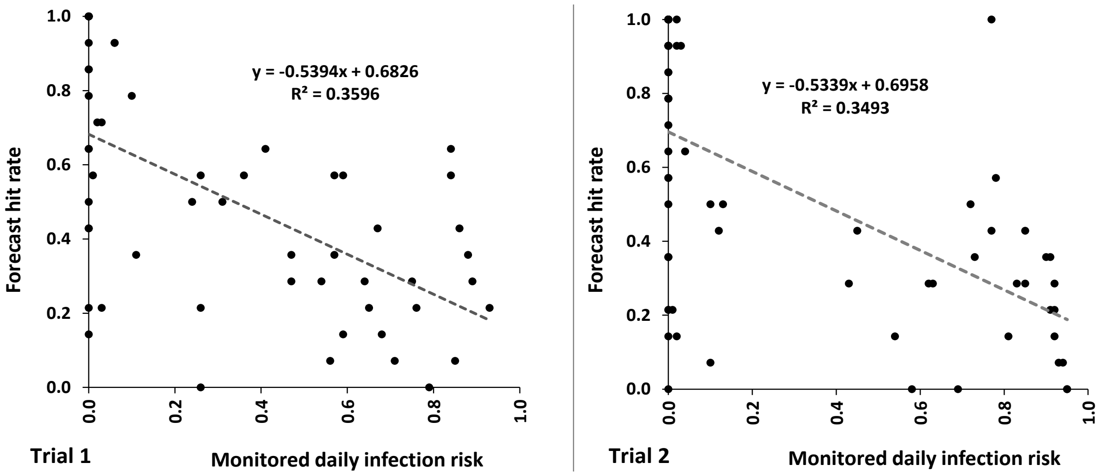


Figure 12. Relationship between the monitored value of daily infection risk and the hit rate (proportion of correct predictions) for infection risk predicted from 14 forecast days ahead of each day of monitored risk. Regression lines for both trials are highly significant ($p < 0.01$; 58 df for Trial 1; 52 df for Trial 2).

4.3 Forecast-based risk analysis discussion

The forecast accuracy analysis shows that the IBM weather forecasts are useful for making accurate spray decisions 1–2 days ahead but that the accuracy drops quickly and would unreliable more than 4–6 days ahead. However, the forecast information provided in the weather-risk tool is still useful further ahead than that because it provides a general indication about incoming periods of higher risk and associated weather that would help some aspects of spray planning.

The accuracy analysis findings were confirmed by the experience of making the spray decisions for Trial 1 and Trial 2. On some occasions, the daily risk forecasts kept changing as a risk threshold was approached and the exact day it would cross the line was difficult to anticipate. The accuracy analysis also showed that the hit rate for a given set of forecasts decreases as cumulative risk approaches the next spray threshold. Accuracy was greatest when risk was in the middle between the previous and the next threshold value.

However, in terms of controlling myrtle rust, whether a spray is applied on the exact day a threshold is crossed or a day either side may not actually matter. These trials used reactive spraying in response to cumulative risk thresholds being reached, rather than pre-emptive spraying ahead of particular days with high risk. The reactive approach is appropriate for myrtle rust because infection occurs more or less continuously, with a high frequency of days suitable for infection over the time scale of expected fungicide re-application intervals.

The finding that forecast accuracy is better during fine periods will provide the nursery manager with peace of mind that unexpected infection events are unlikely during settled weather. However, the poorer prediction of high-risk periods of humid weather suitable for infection is the main limitation of the weather forecast–based risk predictions.

The utility of the risk tool could possibly be improved if there was a way of displaying the degree of confidence in each forecast as it is received. This could be done in terms of the consistency of the set of forecasts ahead of a given monitored Day 0 risk value as that day approaches. It is not possible to predict which out of a given set of 14 forecasts will correctly predict the Day 0 value because that value is not knowable ahead of time.

Bias in the risk predictions made from weather forecasts, i.e., whether they tend to over-predict or under-predict actual risk, could also be studied to help understand the meteorological conditions associated with inaccurate forecasts. Feedback of this information to the forecast providers might be useful in improving forecast accuracy.

5 Fungicide resistance management (Objective 3)

5.1 What is fungicide resistance?

Fungal plant pathogens, such as myrtle rust, can sometimes develop resistance to the modern synthetic fungicides used for controlling the diseases they cause. Resistance results from repeated use of particular fungicides over a period of time, often years and sometimes decades. Older broad-spectrum fungicides are not likely to select resistance.

Resistance is a genetic change in the pathogen that allows it to survive in the presence of a once-lethal dose of fungicide. The change towards resistance occurs because of random natural gene mutations that occasionally produce a pathogen genotype that is better able to survive in the presence of the fungicide. The less sensitive part within the population is selected for by ongoing use of the fungicide and the population gradually shifts towards resistance, possibly to the extent that the fungicide can no longer control the disease. Resistance mutations may involve a single gene or several genes. If strong resistance is conferred by a single gene mutation, then population resistance may develop relatively quickly (e.g., 3-5 years), whereas if several genes are involved, each with a small effect, then a slower and more gradual increase in population resistance is likely (e.g., several decades).

The fungicides that are at risk from resistance are the modern synthetic ones that have a mode of action that inhibits a single biochemical pathway in the pathogen’s metabolism (single-site inhibitors). Fungicides not at risk from resistance are generally older ones, including some synthetic compounds, like mancozeb, and inorganic chemicals like copper. These inhibit multiple biochemical pathways and are called either multi-site inhibitors or broad-spectrum fungicides.

While some fungal pathogens develop resistance quite readily, most rust fungi have not shown this tendency. However, recent genetic research on cereal rusts shows that resistance mutations can be present and suggests the risk of resistance in rusts is greater than previously assumed (Oliver 2014; Cook et al. 2021). Control of myrtle rust in nurseries on vulnerable hosts requires year-round fungicide protection involving up to 20–30 fungicide applications per year, although the number of individual plants requiring protection may be small. If *A. psidii* does have the potential to develop resistance, then the large number of applications is a risk factor. It is therefore important that guidelines for the prevention and management of resistance in myrtle rust are developed.

5.2 Fungicide mode of action groups

Fungicides are grouped according to the way they inhibit the pathogen's metabolism (mode of action) and the various groups are assigned code numbers by the Fungicide Resistance Action Committee (FRAC) in Europe (frac-code-list-2022--final.pdf). There are different chemical compounds (active ingredients) within each mode of action group and although they differ in their chemistry, there is cross-resistance between them, meaning they select resistance in fungal pathogens in the same way. The various active ingredients in a given mode of action group may be marketed in different products with differing formulations. Group codes are displayed prominently on each fungicide product label so that it is clear what group, or groups, each product contains (Figure 13).

Within a mode of action group, different active ingredients vary in their intrinsic fungicidal activity and, because of their different chemistry, they also interact differently with the plant. For example, some may bind to the surface more readily making them less likely to be washed off by rain, or, for groups with systemic activity (i.e., absorbed into the plant), e.g., Group 3 DMIs and Group 11 QoIs, different active ingredients tend to vary in their curative ability on existing infections.

The fungicides currently recommended by NZPPI for myrtle rust management in nurseries (Appendix 3; Download.aspx (nzppi.co.nz)) fall into just three out of the approximately 50 single-site inhibitor groups and three out of 12 multi-site inhibitor groups (Table 3).

A systemic fungicide for control of stripe rust, leaf rust, powdery mildew and speckled leaf blotch in wheat, scald and leaf rust in barley, crown rust in oats, rusts in ryegrass seed crops, powdery mildew in peas and white rot in onions.

Active Ingredient: contains 250g/litre triadimenol in the form of an emulsifiable concentrate. Also contains 1-Methyl 2-pyrrollidinone.

Contains 62.5 g/litre fluxapyroxad in the form of an emulsifiable concentrate

Systemic cereal fungicide for the control of diseases in barley and wheat crops

Contains 250 g/L pyraclostrobin in the form of an emulsifiable concentrate. Also contains 450 g/L hydrocarbon solvents.

Systemic fungicide for the control of diseases in barley, maize, ryegrass and wheat.

Figure 13. Examples of mode of action group codes on fungicide product labels for groups 3 (demethylation inhibitors), 7 (succinate dehydrogenase inhibitors) and 11 (quinone outside inhibitors). These codes make it easy to avoid consecutive or mixed applications of fungicide products within the same mode of action group when following fungicide resistance management guidelines.

Table 3. Fungicides registered in New Zealand and recommended for use against myrtle rust by New Zealand Plant Producers Inc. showing mode of action groups and their code numbers.

[1]FRAC group code	Mode of action	Active ingredient	Solo products	Mixed products	[3]Relative efficacy
Single-site inhibitors					
3	Demethylation inhibitor (DMI)	Triadimenol and others	Vandia® Cereous® Tilt® Opus®	In Scorpio®	+++
7	Succinate dehydrogenase inhibitor (SDHI)	Fluxapyroxad	[2]Elatus® Plus [2]Sercadis®		+
11	Quinone outside inhibitor (QoI)	Azoxystrobin	Amistar® etc.	In Scorpio®	+++
Multi-site inhibitors					
M 01	Copper	Copper hydroxide etc.	Kocide® Opti™ etc.		+

M 03	Dithiocarbamate	Mancozeb	Dithane® Mancozeb etc.	+
M 05	Chloronitriles	Chlorothalonil	Bravo® etc.	+

[1] Fungicide Resistance Action Committee
[2] The current field trials show Sercadis has limited activity against myrtle rust; Elatus Plus needs testing.
[3] +++ = highly effective; ++ = moderately effective; + = slightly effective against myrtle rust

5.3 Principles of resistance management

Resistance development to an at-risk fungicide can often be delayed and, even if it is already developing, it can often be managed. Both of these require limiting exposure of the pathogen to the at-risk fungicide group while still using that type of fungicide to benefit disease control.

Often, when resistance develops, the genetic mutation(s) controlling it result in decreased ability of the pathogen to survive in the absence of the fungicide. This ‘loss of fitness’ may allow resistance to be managed if exposure of the pathogen to that fungicide is reduced. There are four ways to reduce pathogen exposure:

1. Limit the number of applications per year.
2. Mix the at-risk single-site fungicide with a broad-spectrum fungicide that is effective against the pathogen.
3. Mix the at-risk single-site fungicide with and effective dose of another single-site inhibitor in a different mode of action group.
4. Alternate the at-risk fungicide with either an effective dose of a broad-spectrum fungicide or of another single-site inhibitor in a different mode of action group.

Increasingly, fungicide products are being marketed that contain a mixture of two at-risk single-site inhibitors from different groups. This is not ideal because resistance can develop to one and then the other component and when that happens both mode of action groups may be rendered ineffective.

In justifying the sale of products with such mixtures it is sometimes claimed that the activity of a mixture with different mode of action groups gives greater disease control than the additive effect of the two components (i.e., a synergistic effect). If this were the case then there could be an additional benefit for disease control, but only while the pathogen is still sensitive to both groups.

The preferred approach is to mix a single-site inhibitor with an effective dose of a multi-site inhibitor that is not at risk from resistance; however, finding suitable multi-site inhibitors with adequate efficacy is often difficult. Benign or ‘eco-friendly’ chemicals, such as sodium bicarbonate and fatty acid soaps, are not classified by FRAC. There are anecdotes about use of these in the nursery industry against myrtle rust, but their efficacy has not been scientifically tested.

Sometimes products contain mixtures of fungicides within the same group, perhaps because the different active ingredients have slightly different protectant or curative characteristics. These mixtures do not help fungicide resistance management.

Of the fungicides recommended for myrtle rust control, the QoIs are known to select single gene resistance in other pathogens that may cause a complete loss of disease control within a few years. The DMIs select multigene resistance that usually develops as a slow shift over decades towards resistance. The SDHIs have been more recently introduced and several known genes are implicated in resistance development.

5.4 Fungicide resistance management guideline for myrtle rust

- Fungicides in mode of action groups 3 DMI, 7 SDHI and 11 QoI (Table 1) are suitable for controlling myrtle rust but are at risk from resistance. These should be used as follows:
    1. Apply preventatively when disease risk is high and preferably before disease appears.
    2. Make no more than five applications of each at-risk group per year (1 July – 30 June).
    3. Apply each at-risk fungicide either in mixture with an effective dose of a multi-site inhibitor (groups M1, M3 and M5) or in strict alternation with either a single-site fungicide in a different group or, preferably, a multi-site fungicide.
    4. When choosing fungicides, make use of the group codes displayed on product labels to avoid mixed or consecutive applications of the same at-risk mode of action group.
    5. The application rate of a fungicide used for myrtle rust control should be the recommended label rate for that fungicide on an appropriate other crop (Ministry for Primary Industries - ACVM Register (nzfsa.govt.nz)).
    6. An application of a product containing a mixture of two fungicides in the same mode of action group counts as one application towards that group's annual count.
    7. The Environmental Protection Authority (EPA) may specify a maximum number of applications per year for particular fungicide products. This would take priority over the maximum number indicated in this resistance management guideline for any so-specified product. (Controls for hazardous substances | EPA).
- This guideline has been reviewed by the New Zealand Committee on Pesticide Resistance.

6 Myrtle rust spray programme design (Objective 4)

In nurseries, myrtle rust must be completely prevented from developing on vulnerable host species and this requires repeated fungicide spray applications throughout the year, with the frequency varying according to season.

A nursery myrtle rust fungicide spray programme needs to consider the following:

1. Vulnerability of different myrtle species to myrtle rust.
2. Presence of shoot flush on vulnerable species.
3. Nearby sources of infection.
4. Climatic risk, regionally, seasonally, and daily.
5. When fungicides in different mode of action groups are best used.
6. Fungicide resistance management to limit the use of certain fungicide groups.

6.1 Vulnerability of myrtle species

Information about how different myrtle species are affected by myrtle rust in New Zealand is constantly evolving as new observations come to hand. In general, the impact of myrtle rust on our native myrtles is increasing year-on-year, with greater disease severity and new species reported to be infected as the environmental load of the pathogen increases. Appendix 2 shows an assessment of our current understanding about species vulnerability.

Assessing the overall vulnerability of a particular species is challenging because it is affected by the following factors:

1. Genetic susceptibility: Whether the plant’s genetic makeup provides *A. psidii* with the potential to cause infection.
2. Growth flush: Only actively growing plant tissues (leaves, stems flowers and fruit) of myrtle hosts are able to be infected by *A. psidii*.
3. Receptive growth stage: Some species are affected most as young seedlings but others can be affected at any stage of growth when growth flush is present.
4. Whether local environmental conditions are conducive to infection and disease development.

Another complicating factor is that myrtle species, both native and exotic, grown from seed generally exhibit genetic variation in their reaction to myrtle rust. From any given mother plant, some seedlings often appear to be more resistant than others, even though myrtle rust may still cause infection on them all. Appendix 2 also summarises which myrtle species require fungicide protection.

6.1.1 Native myrtles

Many myrtle species are recorded as hosts of myrtle rust in New Zealand (Plant-species-confirmed-to-be-infected-with-myrtle-rust-in-New-Zealand4.pdf (myrtlerust.org.nz)) but not all of these are badly impacted. Below are the New Zealand native species that are proving most vulnerable and for these, plants of any age can suffer severe damage:

- Maire tawake/swamp maire (*Syzygium maire*)

- Ramarama (*Lophomyrtus bullata*)
- Rōhutu (*L. obcordata*)
- Hybrid *Lophomyrtus* sp. (*L. bullata* x *L. obcordata*).

The two *Lophomyrtus* species hybridise naturally and the hybrids are often as genetically susceptible as the parent species, although susceptibility may vary.

Myrtle rust is often damaging on seedlings of young pōhutukawa (*Metrosideros excelsa*), particularly in nurseries, but older trees are generally less affected. Pōhutukawa plants grown from seed vary greatly in their genetic susceptibility.

Of the six species of climbing rātā, there are reports of myrtle rust affecting *Metrosideros colensoi* (Colenso’s rātā), *M. carminea (*carmine rātā; akakura), *M. fulgens* (scarlet rātā*;* akatawhiwhi), *M. perforata* (akatea) and *M. diffusa (*white rātā). These plants appear to become infected when they are growing in close proximity to more susceptible hosts, such as *Lophomyrtus* spp.

Reports of myrtle rust on mānuka (*Leptospermum scoparium*) are few and are mostly of infection on young seedlings. There has been one report of a low incidence of seed capsule infection in Auckland on older mānuka plants grown from seed sourced from the Rotorua Lakes District area.

Current information suggests that mānuka, kānuka, northern rātā and southern rātā do not currently need regular fungicide sprays but young plants of these species should be constantly monitored and a spray programme instigated if myrtle rust is found on them.

6.1.2 Exotic myrtles

A particularly vulnerable exotic species is lilly pilly (*Syzygium australe*), which is popular in the upper North Island as a hedge plant. The identification of different lilly pilly types is challenging but has been clarified by Manaaki Whenua Landcare Research (What's in a name? Demystifying lilly pilly hedges » Manaaki Whenua (landcareresearch.co.nz)).

Guava (*Psidium guajava*) can also be severely affected by myrtle rust. Several other exotic myrtle species, including *Eucalyptus* spp., were recorded with myrtle rust during the initial MPI incursion response but subsequent reports are few (Plant-species-confirmed-to-be-infected-with-myrtle-rust-in-New-Zealand4.pdf (myrtlerust.org.nz)).

6.2 Presence of shoot flush

Because myrtle rust can only infect actively growing shoots, seasonal timing of new shoot flush and myrtle rust epidemics are closely linked. Nursery production, by its nature, requires actively growing plants and so the potential for myrtle rust in nurseries is very high. Plant growth rates of all myrtles are higher at warmer temperatures, so myrtle rust risk is highest in summer. A key question for seasonal fungicide protection is how much growth, if any, can continue during the colder winter months in different regions. For example, previous work (Beresford unpublished) suggests that leaf emergence in pōhutukawa becomes very slow at mean temperatures below about 11°C, whereas *Lophomyrtus* sp. can keep growing under colder conditions and still produce new growth, albeit at a slow rate, down to near 0°C.

Mean winter air temperatures below 11°C occur during June, July, and August in coastal areas south of about Tauranga in the east and New Plymouth in the west (Figure 14). In areas further south, pōhutukawa would not produce new growth flush in winter, although pōhutukawa may be less likely to be grown in more southern areas because it is frost tender and would require frost protection.

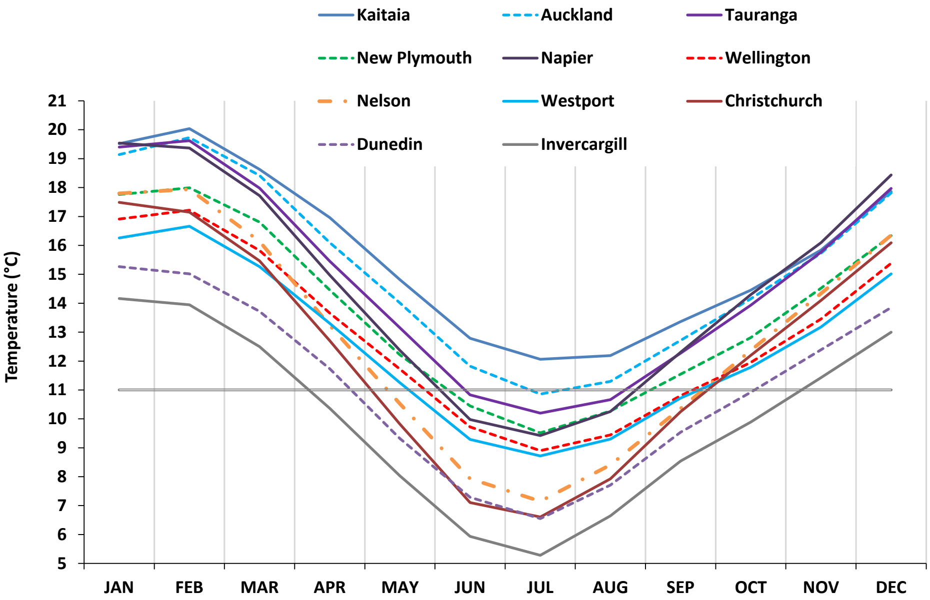


Figure 14. Mean monthly air temperature at selected locations across New Zealand showing where mean winter temperatures less than 11°C occur. Data are from the National Institute of Water and Atmospheric Research.

It is not just presence of growth flush that affects myrtle rust development in winter because the rust fungus itself, while latent inside the host plant, also stops growing at temperatures below about 11°C (i.e., the latent development rate approaches zero) (Beresford et al. 2020).

For some species, e.g., *Lophomyrtus* spp., the temperature at which myrtle rust stops developing has been shown to be higher than that at which the plant stops growing. This would allow *Lophomyrtus* sp. a period of slow growth free from new myrtle rust infection during winter in some areas. For pōhutukawa, plant growth and myrtle rust latent development both appear to stop at around the same temperature. We do not have this type of information for other myrtle species but it would be valuable to better understand the need for fungicide protection of different species during winter in different regions.

6.3 Sources of infection

Myrtle rust is only transmitted by the spores produced in pustules on infected stems leaves flowers and fruit. The main spore type (urediniospores) are dry, wind-borne spores, although they can also be transferred mechanically via clothing, equipment, etc. They do not survive for long in the soil and in the natural environment will last at most a few days on plant surfaces if they do not infect a vulnerable host.

Myrtle rust can be transported to nurseries in symptomless infected plant material and nursery biosecurity measures are crucial to prevent that happening. Myrtle rust will most likely arrive in a nursery via wind-blown spores from nearby infected Myrtaceae plants, e.g., rust-infected native and exotic species in hedges, gardens or wild areas. A major source of infection in the upper North Island is believed to be hedges of exotic lilly pilly (*Syzygium australe*). Other likely sources are native *Lophomyrtus* or pōhutukawa plants, although spore production from pōhutukawa appears to be very much less than from lilly pilly and *Lophomyrtus*. It can be difficult to detect local sources of infection and even more difficult to have them removed.

The most likely source of infection is the closest infected myrtle plant, and it is important to be able to identify vulnerable myrtles within a 500-m radius of a nursery. Good hygiene within the nursery is also very important and old nursery stock of vulnerable myrtles should be disposed of promptly.

Myrtle rust is most likely to establish within a nursery during favourable weather conditions, as can be identified by the online weather-risk tool. There is a delay between when infection occurs and when new myrtle spores appear (the latent period) and it could take one or more cycles of re-infection before rust becomes detectable. Regular surveillance of myrtles in a nursery is essential for early detection (e.g., weekly in summer and every 3–4 weeks in winter in cooler areas). If myrtle rust is found, all symptomatic material (i.e., anything with yellow spore pustules) must be removed into sealed bags immediately. Spore production continues whenever active spore pustules are present so there is a high risk of further infection until they are removed. Good nursery hygiene is important, including sanitising equipment (see System Protocols - NZPPI))

6.4 Regional and seasonal climatic risk

Myrtle rust risk is higher in the upper North Island and lower in the South Island and in higher altitude areas. It tends to be slightly greater in western areas than eastern areas of both the North and South Islands. Regional and seasonal trends in climatic risk, as it determines the need for fungicide protection, are shown in Figure 15.

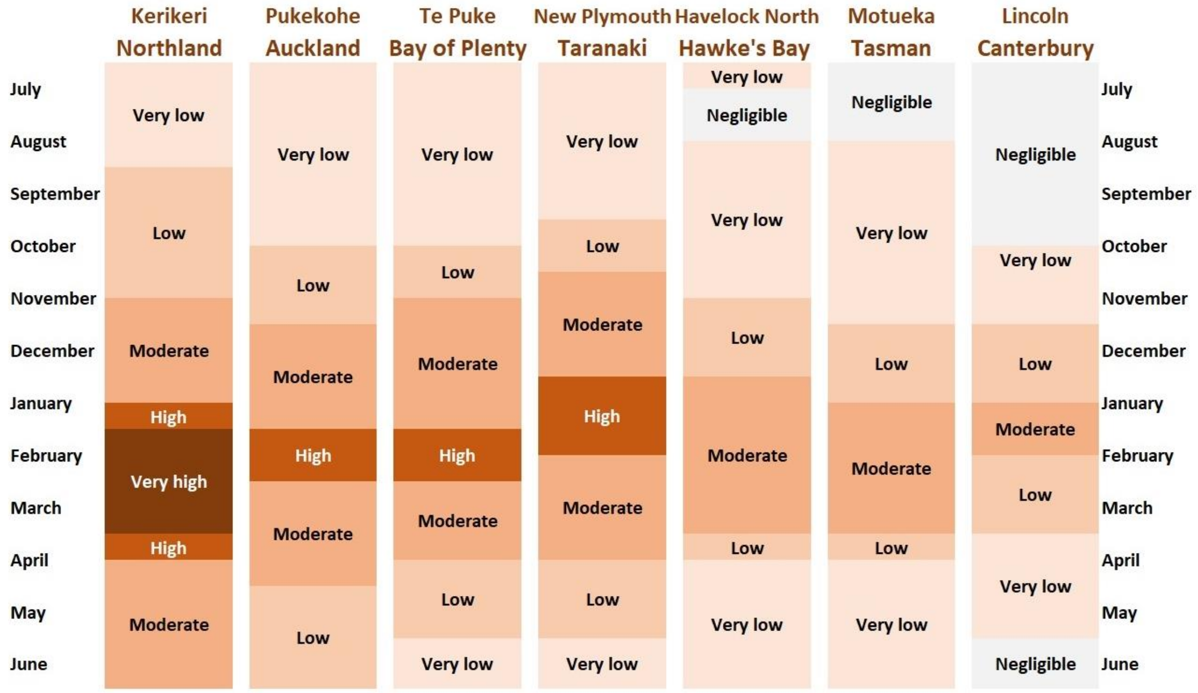


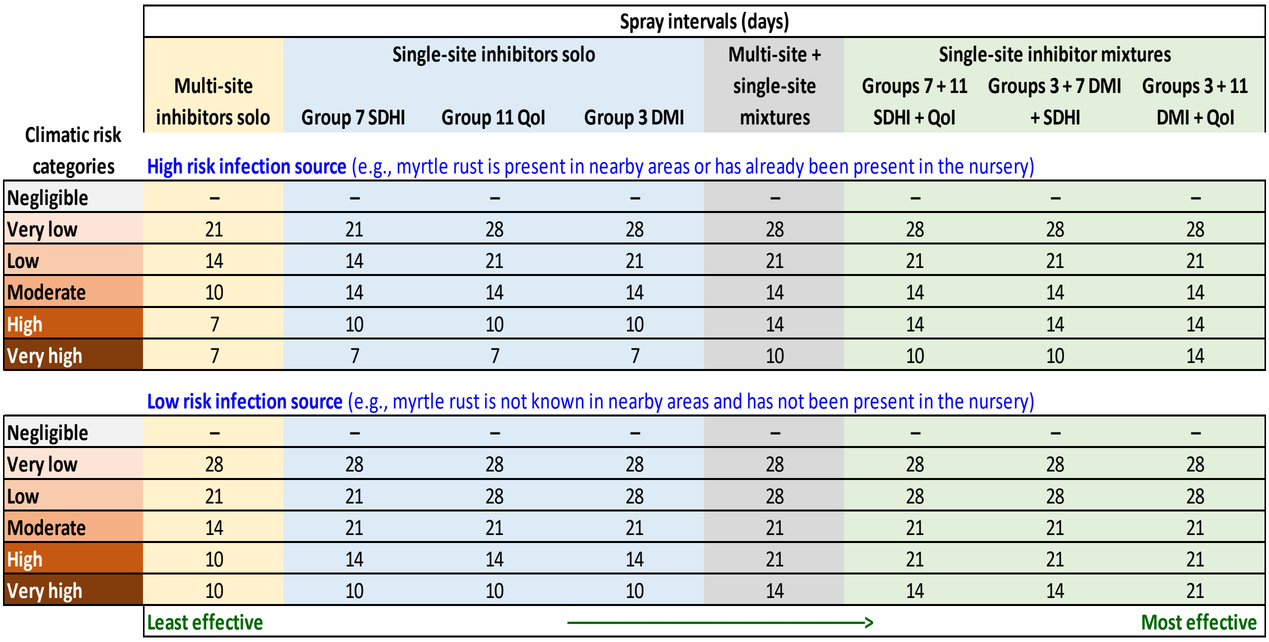
Figure 15. Summary of average myrtle rust climatic risk over 6 years (2016–22) at selected locations in seven New Zealand regions as it affects the need for nursery fungicide spraying to protect highly vulnerable myrtle species. Information based on

daily overall risk calculations for each location, where negligible = 0–0.002; Very low = 0.0020–0.015; Low = 0.015–0.03; Moderate = 0.03–0.05; High = 0.05–0.07; Very high = >0.07.

6.5 Selection of fungicides and spray intervals

Different fungicide groups differ in their type of activity against myrtle rust (Table 3) and spray intervals need to be shorter when fungicide efficacy is lower or disease risk is higher. Fungicide mixtures of single-site inhibitors, particularly Group 3 DMI and Group 11 QoI, give very strong suppression of myrtle rust but are not preferred from a resistance management perspective. However, their occasional use may be justified under very high disease risk. Some fungicides (e.g., copper) risk causing plant damage (phytotoxicity) and the higher the application rate, the greater the risk.

A rule-of-thumb guide for how fungicide groups and their combinations can be selected and how spray re-application intervals can be determined for different risk situations are shown in Figure 16, with the rationale explained below. When the weather-risk tool is being used, the effect of climatic risk on the optimum spray re-application interval is identified automatically.



	Spray intervals (days)							
		Single-site inhibitors solo			Multi-site + single-site mixtures	Single-site inhibitor mixtures		
Climatic risk categories	Multi-site inhibitors solo	Group 7 SDHI	Group 11 QoI	Group 3 DMI		Groups 7 + 11 SDHI + QoI	Groups 3 + 7 DMI + SDHI	Groups 3 + 11 DMI + QoI
	High risk infection source (e.g., myrtle rust is present in nearby areas or has already been present in the nursery)							
Negligible	–	–	–	–	–	–	–	–
Very low	21	21	28	28	28	28	28	28
Low	14	14	21	21	21	21	21	21
Moderate	10	14	14	14	14	14	14	14
High	7	10	10	10	14	14	14	14
Very high	7	7	7	7	10	10	10	14
	Low risk infection source (e.g., myrtle rust is not known in nearby areas and has not been present in the nursery)							
Negligible	–	–	–	–	–	–	–	–
Very low	28	28	28	28	28	28	28	28
Low	21	21	28	28	28	28	28	28
Moderate	14	21	21	21	21	21	21	21
High	10	14	14	14	21	21	21	21
Very high	10	10	10	10	14	14	14	21
	Least effective			——————>				Most effective

Figure 16. Rule-of-thumb guide to spray re-application intervals for different fungicide mode of action groups applied to highly vulnerable myrtle species in relation to myrtle rust climatic risk categories. The upper part represents higher risk where a source of nearby infection is likely and the lower part represents lower risk where a nearby infection source is unlikely. A dash indicates no spray is required.

6.5.1 Periods of high and very high risk

The focus should be on single-site inhibitors during high and very high-risk periods, although multi-site inhibitors, while less effective, should also be used to help prevent fungicide resistance to single-site inhibitors and to provide added protectant activity to fungicide applications.

Group 3 DMI fungicides

Group 3 DMI fungicides (azoles or triazoles) are the most effective against myrtle rust and of these, triadimenol (e.g., Vandia, Jupiter, etc.) consistently performs the best. Although many others are also very effective, older DMIs, e.g., triforine (Saprol®) may be less effective.

DMIs are systemic (absorbed into the plant) providing curative activity that allows them to ‘reach back’ and inhibit infection that happened up to 3–4 days ago. The degree of curative activity varies with different active ingredients and product formulations. A fungicide may persist systemically within the plant longer at low winter temperatures when growth is very slow or static. New shoot growth decreases curative activity as the fungicide concentration within the plant becomes diluted. The same applies to protectant activity as new unprotected shoot tissues emerge.

The Group 11 QoI fungicides

QoI fungicides (strobilurins) are highly effective with curative and protectant activity and with good persistence on plant surfaces. Differences in the activity of different QoI active ingredients against myrtle rust have not yet been determined.

Group 7 SDHI fungicides

The Group 7 SDHI fungicides generally have a degree of systemic curative activity. The active ingredient tested in this study, fluxapyroxad as two different formulations (Sercadis and Comet) and at two different rates, did not perform strongly. Overseas work has only tested the first generation SDHI, oxycarboxin and that was not effective against myrtle rust. Further testing of other newer SDHIs, including Elatus Plus is needed. The spray trials in this study suggest SDHIs should be used at the high end of application rates recommended on product labels and the short end of the re-application intervals.

Groups M1, M3 and M5 multi-site inhibitors

The multi-site inhibitor broad-spectrum fungicides are useful during high and very high-risk periods as mixing and alternation partners with the single-site groups. Mixing enhances the protectant ability of any fungicide application and reduces the risk of fungicide resistance. Multi-site inhibitors used alone require shorter re-application intervals than effective single-site inhibitors.

6.5.2 Periods of moderate risk

When disease risk is not high or very high, there should be less emphasis on single-site inhibitors and more emphasis on multi-site inhibitors to help comply with resistance the management guideline of no more than five applications of each single-site inhibitor group per year. This applies less in cooler southern areas where maximum annual risk is only moderate (Figure 15), making it is easier to comply with the resistance management guideline.

6.5.3 Periods of low or very low risk

Multi-site inhibitors should be used at relatively long re-application intervals and the focus should be on products with long persistence under wet and rainy conditions, e.g., copper oxychloride. A single-site inhibitor may be used under low-risk conditions if myrtle rust is known to be present, preferably in mixture with a multi-site inhibitor.

6.5.4 Periods of negligible risk

No fungicide applications should be required when risk is categorised as negligible because it is generally too cold for *A. psidii* infection and the latent development rate is close to zero.

6.5.5 Example fungicide programmes

Product labels give guidance on re-application intervals for various crops, but there is no guidance for myrtle rust on Myrtaceae plants. Although less effective fungicides require shorter re-application intervals, it is generally not necessary to spray at less than 7-day intervals. This is because, unless there is exceptional rainfall just after spraying, the fungicide residue provides adequate protection for about a week. The main reason for fungicide re-application every 7–10 days is to protect new shoot tissue during periods of rapid growth.

Hypothetical spray programmes were constructed for two areas with contrasting climatic risk (Northland and Canterbury) (Figure 17) by applying the re-application intervals in Figure 16 to the regional climatic risk categories in Figure 15 while complying with resistance management guidelines for single-site inhibitors. This illustrates the huge difference in myrtle rust spraying requirements that can be expected across New Zealand's climatic range.

Kerikeri, Northland (Infection sources risk = High)

Month	Climatic risk	Spray no.	Fungicide Spray date	Interval to next spray (days)	Fungicide mode of action group
July	**Very low**	1	1-Jul-22	21	M1 copper
		2	22-Jul-22	21	M1 copper
August		3	12-Aug-22	21	M1 copper
September	**Low**	4	2-Sep-22	14	M1 copper
		5	16-Sep-22	21	11 QoI
October		6	7-Oct-22	14	M3 mancozeb
		7	21-Oct-22	21	3 DMI
November		8	11-Nov-22	14	M3 mancozeb
	Moderate	9	25-Nov-22	14	7 SDHI
December		10	9-Dec-22	14	3 DMI + M3 mancozeb
		11	23-Dec-22	14	11 QoI
January		12	6-Jan-23	10	M3 mancozeb
		13	16-Jan-23	14	3 DMI + 11 QoI
	High	14	30-Jan-23	7	M3 mancozeb
February	**Very high**	15	6-Feb-23	7	7 SDHI
		16	13-Feb-23	7	11 QoI
		17	20-Feb-23	7	M3 mancozeb
		18	27-Feb-23	14	3 DMI + 11 QoI
March		19	13-Mar-23	14	7 SDHI + mancozeb
		20	27-Mar-23	14	3 DMI + M3 mancozeb
April	**High**	21	10-Apr-23	14	M3 mancozeb
	Moderate	22	24-Apr-23	7	M3 mancozeb
May		23	1-May-23	14	7 SDHI +M3 mancozeb
		24	15-May-23	10	M3 mancozeb
		25	25-May-23	14	7 SDHI
June	**Low**	26	8-Jun-23	14	M1 copper
		27	22-Jun-23	14	M1 copper

Lincoln, Canterbury (Infection sources risk = Low)

Month	Climatic risk	Spray no.	Fungicide Spray date	Interval to next spray (days)	Fungicide mode of action group
July	**Negligible**				
August					
September					
October					
	Very low	1	15-Oct-21	28	M1 copper
November		2	12-Nov-21	28	M1 copper
December	**Low**	3	10-Dec-21	28	11 QoI
		4	31-Dec-21	21	7 SDHI
January	**Moderate**	5	21-Jan-22	21	3 DMI
February		6	4-Feb-22	14	M3 mancozeb
March	**Low**	7	4-Mar-22	28	11 QoI
April	**Very low**	8	1-Apr-22	28	3 DMI
		9	29-Apr-22	28	7 SDHI
May		10	27-May-22	28	M3 mancozeb
June	**Negligible**				

Fungicide spray programme summary

Kerikeri, Northland		**Lincoln, Canterbury**	
Sprayer passes	**27**	**Sprayer passes**	**10**
Product applications	**33**	**Product applications**	**10**
DMIs	**5**	**DMIs**	**2**
QoIs	**5**	**QoIs**	**2**
SDHIs	**5**	**SDHIs**	**2**
Multi-site	**18**	**Multi-site**	**4**

Figure 17. Modelled spray programmes for protecting highly vulnerable myrtle species against myrtle rust in Northland and Canterbury plant nurseries. The Northland spraying intervals assume there is a high risk of nearby infection sources for myrtle rust and the Canterbury example assumes a low infection sources risk. Resistance management guidelines stipulate no more than five applications per year of single-site inhibitor fungicides (demethylation inhibitor; DMI, quinone outside inhibitor; QoI and succinate dehydrogenase inhibitor; SDHI) and their use in strict alternation or mixed applications.

6.5.6 Annual variation in spraying requirements

There is considerable variation in weather patterns and therefore in myrtle rust climatic risk between years. The effect of this on the number of fungicide sprays per year required to control myrtle rust in different regions was modelled using 6 years of climatic risk data (July–June), from 2016–17, when myrtle rust was first detected in New Zealand, to 2021–22. This used the weather-risk tool's cumulative overall risk threshold of 0.5 risk unit increments per spray application.

The modelling identified 2 years with unusually high risk, 2017–18 and 2021–22 (Figure 18) and both these years were associated with marine heatwave conditions (Special Climate Statement 2017-18 Summer | NIWA, Summer 2021-22 | NIWA). Very large differences in spraying requirements were predicted between regions, as shown in Figure 18 and also above in Figure 17.

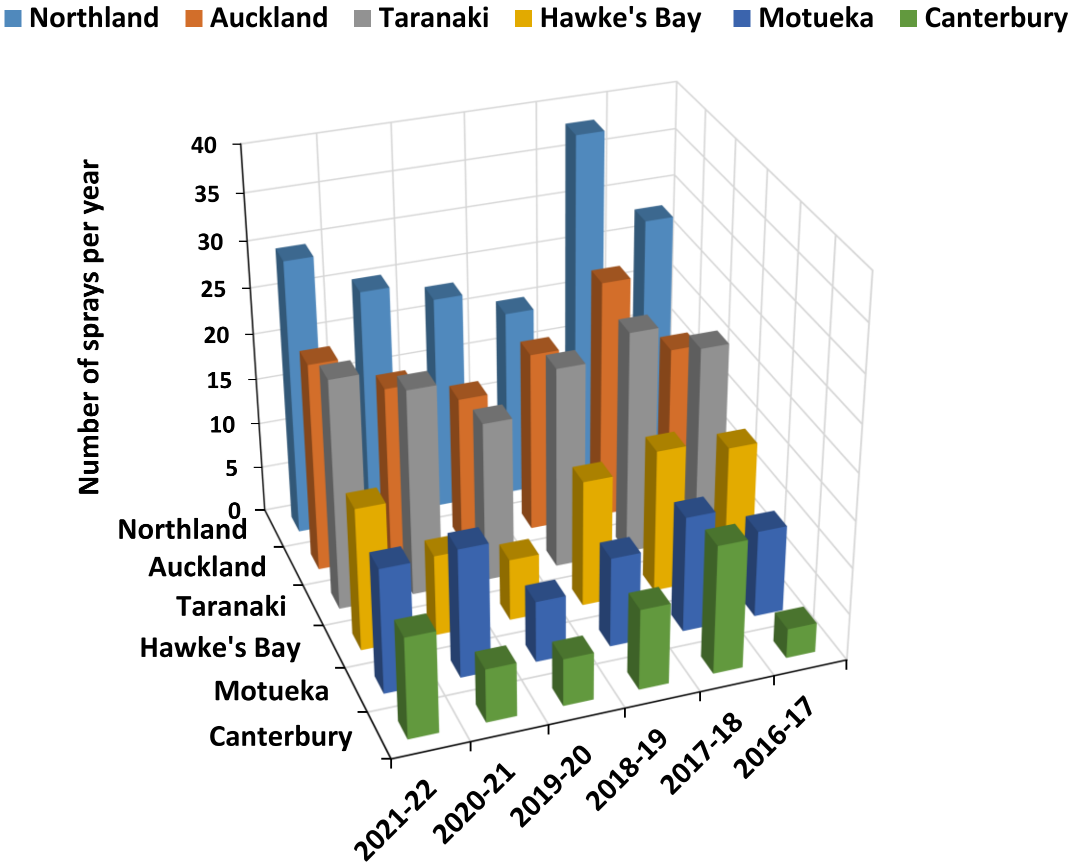


Figure 18. Variation in myrtle rust spraying requirements in different regions over the last 6 years modelled from regional climatic risk analysis and spray re-application intervals using the weather-risk tool's cumulative overall risk threshold of 0.5 cumulative overall risk units between spray applications.

6.6 Fungicide resistance management

Fungicide resistance is fully explained in Section 4 (Fungicide resistance management strategy). Here we just reiterate to not rely on single-site inhibitors to control existing infections. Resistance to single-site inhibitors is most likely to develop when disease has become severe. These fungicides should only be used to prevent infection when disease risk is high but visible disease is either absent or at a low incidence. High disease risk occurs when:

- the weather is warm and humid (as identified by the weather-risk tool);
- new growth flush is present on plants of a genetically susceptible myrtle species;
- there are nearby sources of myrtle rust spores.

6.7 Further refinement of the weather-risk tool

There are several findings from this study that suggest changes to improve the weather-risk tool, as discussed in Sections 6.1 and 6.2.

6.8 Varying the risk increment to alter spraying thresholds

While the current cumulative overall risk increment in the weather-risk tool of 0.5 appeared to be about right for the number of spray applications it generated annually, some sprays applied in the upper North Island during high-risk periods would be at less than 7-day intervals, which could be unnecessarily frequent. Therefore, it would be beneficial to incorporate a minimum re-application interval within the tool. Furthermore, the findings from using the weather-risk tool in the spray trials suggested spraying thresholds should be adjusted slightly for fungicides with different efficacy against myrtle rust.

Spraying thresholds could be adjusted within the tool through user inputs of spray date and fungicide product and an unseen table within the model that relates product efficacy to minimum spray interval and re-calculates the next spray threshold.

6.9 Other risk factors to incorporate

The user interaction with the weather-risk tool could include input of species vulnerability to myrtle rust and proximity or intensity of infection sources. Both these could be included by either scaling the cumulative overall risk output value or by altering the cumulative overall risk increment. However, there are currently no data that could be used to model the effects of species vulnerability or infection sources risk so such changes should be considered carefully. Experience shows that that excessive complexity in decision support tools is usually a disincentive to user uptake.

7 Conclusions and recommendations

Spray trials

- The fungicide spray trials confirmed that Group 3 DMI fungicides are the most effective against myrtle rust, particularly triadimenol, and Group 11 QoI fungicides are also highly effective. Further work is required to determine how effective Group 7 SDHI fungicides are for myrtle rust control. The broad-spectrum fungicides, mancozeb and copper hydroxide performed poorly compared with the nil-fungicide treatment but multi-site inhibitors like these still have a use in myrtle rust spray programmes for fungicide resistance management.
- The weather-risk tool’s spray thresholds at 0.5 cumulative overall risk increments appeared to be appropriate and weather-risk spraying in both summer and autumn gave disease control that was not significantly different from 14-day calendar spraying. The lack of significant differences between spraying strategies could have been partly due to high variability in the trial data and insufficient statistical power in the trial design to detect subtle effects from spray timing differences. Greater replication of treatments should be used in future spray trials.
- The spray trials were conducted under severe disease pressure with myrtle rust always present in the experimental plants. In a nursery situation, where fungicides aim to prevent initial infection of healthy plants, longer spray intervals and fewer sprays per year than indicated in this study may be adequate. NZPPI may be able to investigate this over time by involving nursery managers nationally in observing myrtle rust outcomes associated with their use of the myrtle rust weather-risk tool.
- Disease assessment of myrtle rust in outdoor trials such as these is challenging because disease severity fluctuates with the repeated cycles of shoot growth, infection, shoot death, re-growth and reinfection that occur in highly vulnerable species. Interpretation of myrtle rust disease impacts and the effectiveness of control measures must be cognisant of how cycles of shoot growth and infection affect the timing and methods of disease assessment.

Climatic factors

- The weather forecast–based risk predictions by the weather-risk tool were accurate enough to confidently make spray decisions 1–3 days ahead of when a weather-risk spray threshold would be exceeded. From about 4–6 days ahead, the forecast accuracy was not sufficient for reliable advanced spray decisions and for 7–14 days ahead the predictions were misleading.
- The coverage area of a weather station allowing weather data at other sites accurate enough for spray timing was not examined in this study; however, it is known to depend on local land and other features that affect microclimate. As a rule-of-thumb, coverage is generally adequate within about a 10-km radius from weather stations in topographically uniform areas, whereas in areas with hills and valleys, this may decrease to a radius of 2–5 km. However, despite microclimatic variability, major myrtle rust risk periods tend to occur when northerly quarter wind flows bring several days of high humidity. These conditions generally occur on a region-wide scale and they contrast markedly with the low humidity conditions associated with southerly quarter wind flows, thus micro-climate differences may be less important than is often assumed.

Spray programme design and fungicide resistance management

- It was estimated that fungicide spray programmes to protect vulnerable myrtle species will require, on average, about 27 applications per year in a very high-risk climate such as Northland's and only about 10 per year in a low-risk climate like Canterbury's. However, it is possible that fewer sprays per year might be adequate for the protection of healthy plants in situations of low myrtle rust risk, as mentioned above.
- A draft guideline for the prevention and management of fungicide resistance in *Austropuccinia psidii* has been developed and this has been reviewed by the New Zealand Committee on Pesticide Resistance.
- It is important for spray operators to understand mode of action group codes on fungicide product labels to help avoid consecutive or mixed applications of fungicide products within the same mode of action group when following resistance management guidelines.

Host plant vulnerability

- The advisability of nursery production of highly vulnerable native myrtles, such as *Lophomyrtus* spp. and *Syzygium maire*, is sometimes questioned because these species are likely to become infected by myrtle rust in the natural environment. However, it is a real possibility that nursery production may be all there is between survival and eventual local or national extinction of these species. Species of *Metrosideros* and possibly mānuka appear to be most susceptible as young plants and they may develop natural resistance as they age after leaving the nursery. This growth stage–related vulnerability needs further investigation to understand when and how it develops.
- The exotic lilly pilly (*Syzygium australe*) is a very popular hedge species in the upper North Island but is vulnerable to myrtle rust, which it harbours, and provides area-wide inoculum that threatens vulnerable native species. Nursery production of *S. australe* should be strongly discouraged and there are alternatives including New Zealand natives, like *Pittosporum* spp. (Planting to prevent myrtle rust (aucklandcouncil.govt.nz)).

Weather risk tool refinement

- The weather-risk tool needs to be able to adjust the spray re-application interval according to fungicide product efficacy.
- The vulnerability of different myrtle species to myrtle rust and the proximity of nurseries to sources of infection could both be incorporated into the weather-risk tool.
- Previous experience shows that the uptake of weather-risk decision support tools by horticulture industry user groups is typically low (e.g., 25%). However, these tools generally have a greater influence on industry sector learning about disease management than the uptake rate suggests. Such tools can eventually come to influence almost all fungicide spraying decisions that occur.

8 Acknowledgements

We gratefully acknowledge the Ministry for Primary Industries for funding this project. We wish to thank New Zealand Plant Producers Inc. for providing helpful information about nursery production and HortPlus Ltd for implementing the Myrtle Rust Process Model as an online tool. Working with these organisations has been both positive and productive. The potted plants used in the spray trials were supplied by Stephen Hoyte and colleagues at PFR, Ruakura.

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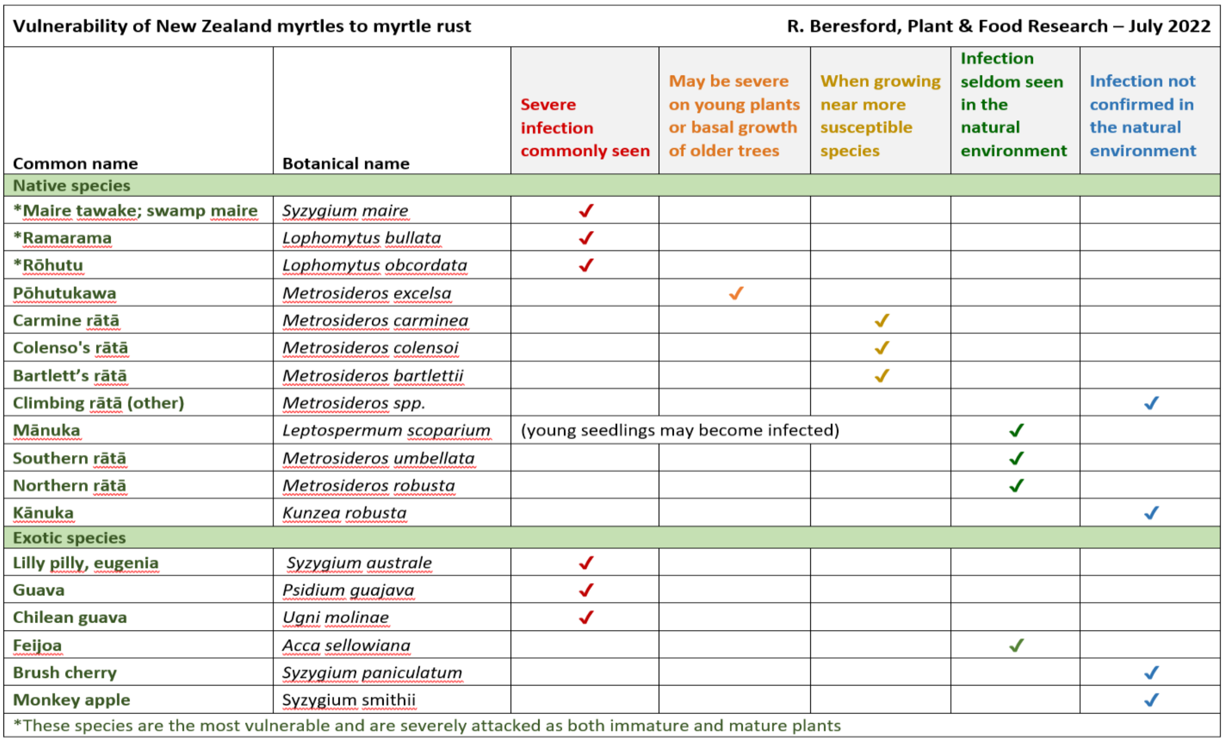
Appendix 1

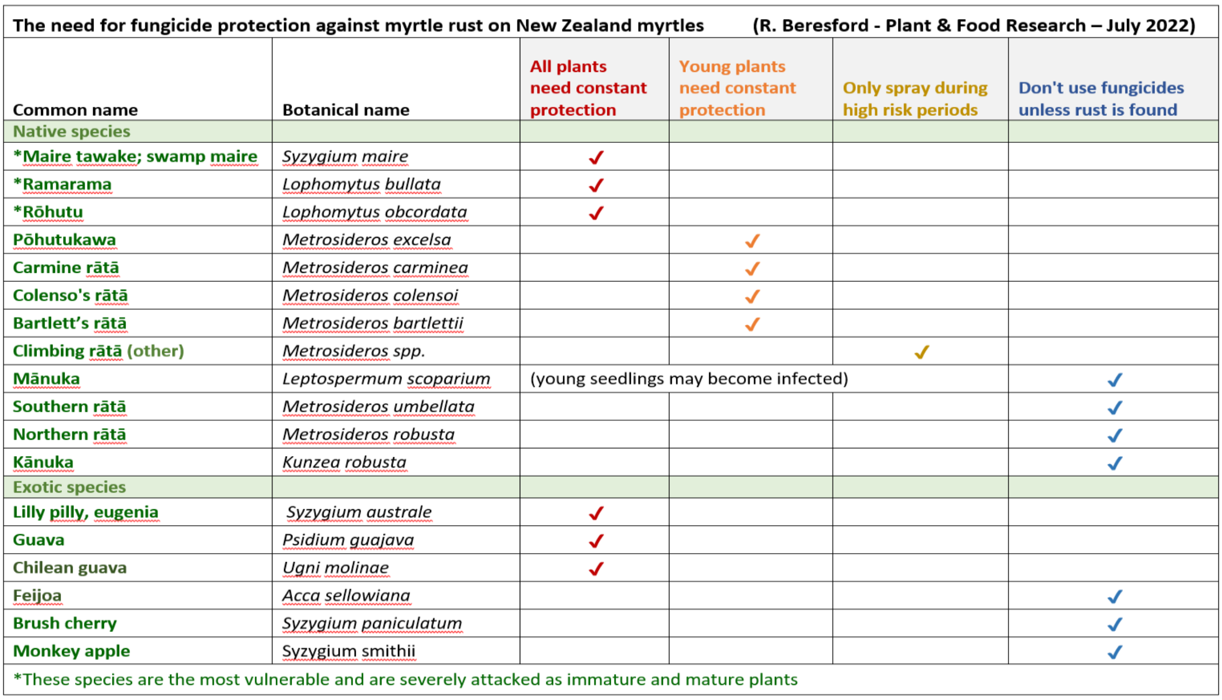
Vulnerability of Myrtaceae species to myrtle rust and the need for fungicide protection in nurseries.



Vulnerability of New Zealand myrtles to myrtle rust — **R. Beresford, Plant & Food Research – July 2022**

Common name	Botanical name	Severe infection commonly seen	May be severe on young plants or basal growth of older trees	When growing near more susceptible species	Infection seldom seen in the natural environment	Infection not confirmed in the natural environment
Native species						
***Maire tawake; swamp maire**	*Syzygium maire*	✓				
***Ramarama**	*Lophomytus bullata*	✓				
***Rōhutu**	*Lophomytus obcordata*	✓				
Pōhutukawa	*Metrosideros excelsa*		✓			
Carmine rātā	*Metrosideros carminea*			✓		
Colenso's rātā	*Metrosideros colensoi*			✓		
Bartlett's rātā	*Metrosideros bartlettii*			✓		
Climbing rātā (other)	*Metrosideros spp.*					✓
Mānuka	*Leptospermum scoparium*	(young seedlings may become infected)			✓	
Southern rātā	*Metrosideros umbellata*				✓	
Northern rātā	*Metrosideros robusta*				✓	
Kānuka	*Kunzea robusta*					✓
Exotic species						
Lilly pilly, eugenia	*Syzygium australe*	✓				
Guava	*Psidium guajava*	✓				
Chilean guava	*Ugni molinae*	✓				
Feijoa	*Acca sellowiana*				✓	
Brush cherry	*Syzygium paniculatum*					✓
Monkey apple	Syzygium smithii					✓

*These species are the most vulnerable and are severely attacked as both immature and mature plants



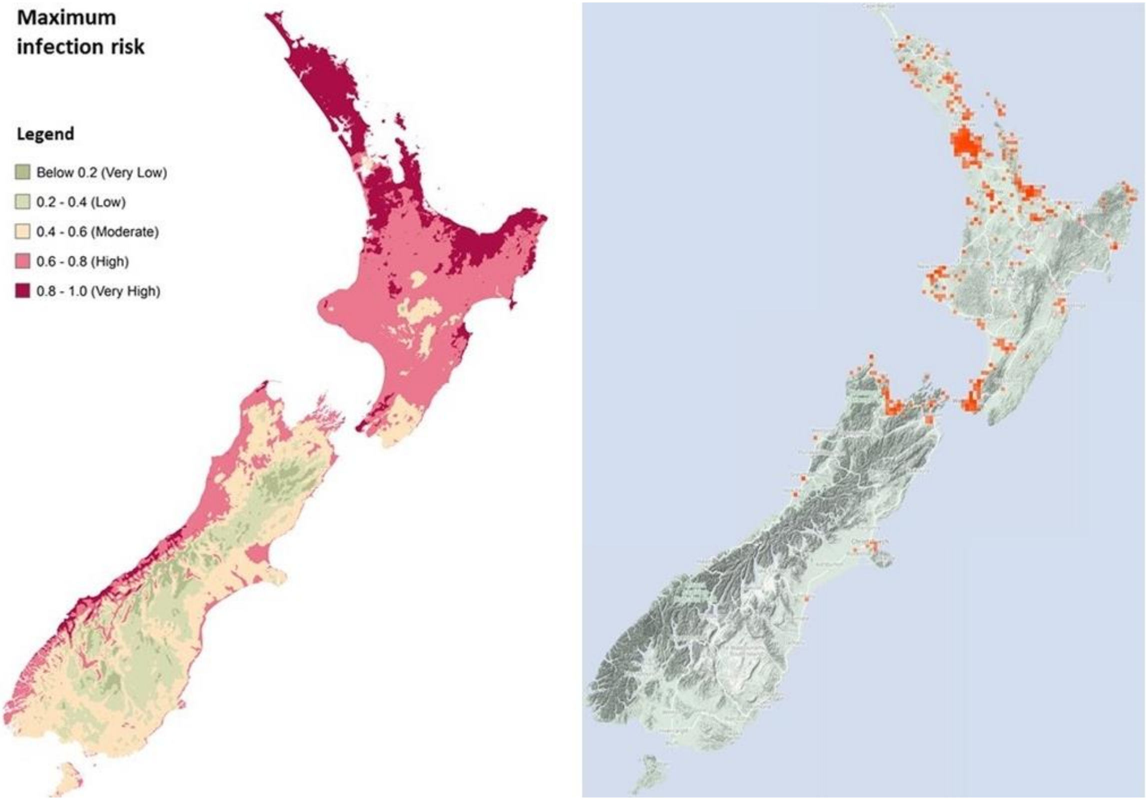
The need for fungicide protection against myrtle rust on New Zealand myrtles — **(R. Beresford - Plant & Food Research – July 2022)**

Common name	Botanical name	All plants need constant protection	Young plants need constant protection	Only spray during high risk periods	Don't use fungicides unless rust is found
Native species					
***Maire tawake; swamp maire**	*Syzygium maire*	✓			
***Ramarama**	*Lophomytus bullata*	✓			
***Rōhutu**	*Lophomytus obcordata*	✓			
Pōhutukawa	*Metrosideros excelsa*		✓		
Carmine rātā	*Metrosideros carminea*		✓		
Colenso's rātā	*Metrosideros colensoi*		✓		
Bartlett's rātā	*Metrosideros bartlettii*		✓		
Climbing rātā (other)	*Metrosideros spp.*			✓	
Mānuka	*Leptospermum scoparium*	(young seedlings may become infected)			✓
Southern rātā	*Metrosideros umbellata*				✓
Northern rātā	*Metrosideros robusta*				✓
Kānuka	*Kunzea robusta*				✓
Exotic species					
Lilly pilly, eugenia	*Syzygium australe*	✓			
Guava	*Psidium guajava*	✓			
Chilean guava	*Ugni molinae*	✓			
Feijoa	*Acca sellowiana*				✓
Brush cherry	*Syzygium paniculatum*				✓
Monkey apple	Syzygium smithii				✓

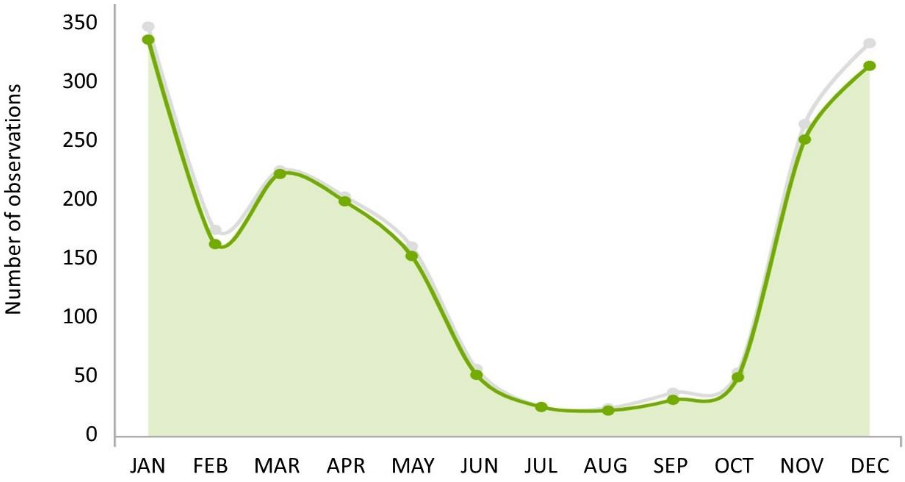
*These species are the most vulnerable and are severely attacked as immature and mature plants

Appendix 2

Myrtle rust maximum summer infection risk predicted by the Myrtle Rust Process Model (Beresford et al. 2018) (left) and the geographic distribution of myrtle rust, as at 17 June 2022, according to iNaturalist (Observations · iNaturalist NZ) (right). Differences between observed distribution and predicted climatic risk suggest myrtle rust may still be spreading southwards. The density of observations partly reflects the distribution of observers.



Annual distribution of myrtle rust observations in New Zealand according to iNaturalist (17/06/2022; all New Zealand observations). Grey line is unverified observations; green line is verified observations.



Appendix 3

Glossary of terms relating to fungicides and fungicide resistance

Active ingredient (active constituent). The component(s) in a formulated fungicide product that specifically inhibit the target pathogen. Formulated products also contain other chemicals to achieve effective delivery of the active ingredient to the plant. The active ingredient is known by its fungicide common name (e.g., triadimenol). Most active ingredients have different degrees of fungicidal activity on different types of fungal pathogens.

Curative (systemic). A fungicide active ingredient that is absorbed into the plant and inhibits the pathogen within the plant tissues after infection has occurred. Such fungicides generally have a limited time after infection has occurred to ‘cure’ the infection (e.g. 1-3 days). This is often referred to as the ‘reach-back’ or ‘kick-back’ interval or period. ‘Systemic’ means within the plant tissue and is often used synonymously with ‘curative’. Curative/systemic fungicides may also be effective protectants.

Eradicant. A fungicide that kills existing fungal lesions on the plant. Eradicant is sometimes used synonymously with curative, but eradicants are not necessarily absorbed into the plant. Eradicants are often older multi-site inhibitor fungicides.

Demethylation inhibitors (DMIs). A group of single-site inhibitor fungicides with a mode of action that blocks the demethylation step in sterol biosynthesis necessary for chitin cell wall formation in fungi. These are also often referred to as azole or triazole fungicides, based on their chemistry.

Fungicide resistance. A genetic change in a pathogen, which was previously sensitive to a particular fungicide, making it less sensitive after that fungicide has been used repeatedly. Practical resistance develops when a major loss of sensitivity in the pathogen population causes a loss of disease control.

Mode of action (MOA). The biochemical pathway(s) within fungal cells inhibited by a particular fungicide. The Fungicide Resistance Action Committee (FRAC) in Europe assigns a code number to each MOA (frac-code-list-2022--final.pdf) and all the active ingredients within a MOA group generally display the code number(s) on the product label. When fungicide resistance develops in a pathogen to a particular fungicide, then all the active ingredients within the same MOA group are expected to be affected by that resistance. However, in practice different active ingredients within a MOA group are often affected by resistance slightly differently.

Multi-site inhibitors. Older fungicides that inhibit many metabolic pathways in the target pathogen (also known as broad spectrum fungicides). These are generally not at risk from development of resistance in the pathogen.

Protectant. A fungicide that is only active against the pathogen on the plant surface where it prevents infection.

Quinone outside inhibitors (QoIs; strobilurin). A group of single-site inhibitor fungicides with a mode of action that blocks mitochondrial respiration in fungal cells at the quinone outside binding site of the cytochrome bc_1 complex.

Single-site inhibitors. Modern synthetic fungicides that inhibit a specific metabolic pathway in the target pathogen. These are often at risk from development of fungicide resistance in the pathogen.

Succinate dehydrogenase inhibitors (SDHIs) A group of single-site inhibitor fungicides with a mode of action that blocks mitochondrial respiration in fungal cells by inhibiting the succinate dehydrogenase enzyme that catalyses the oxidation of succinate into fumarate in the Krebs cycle.

Appendix 4

NZPPI fungicide list for myrtle rust (December 2021) (Download.aspx (nzppi.co.nz).

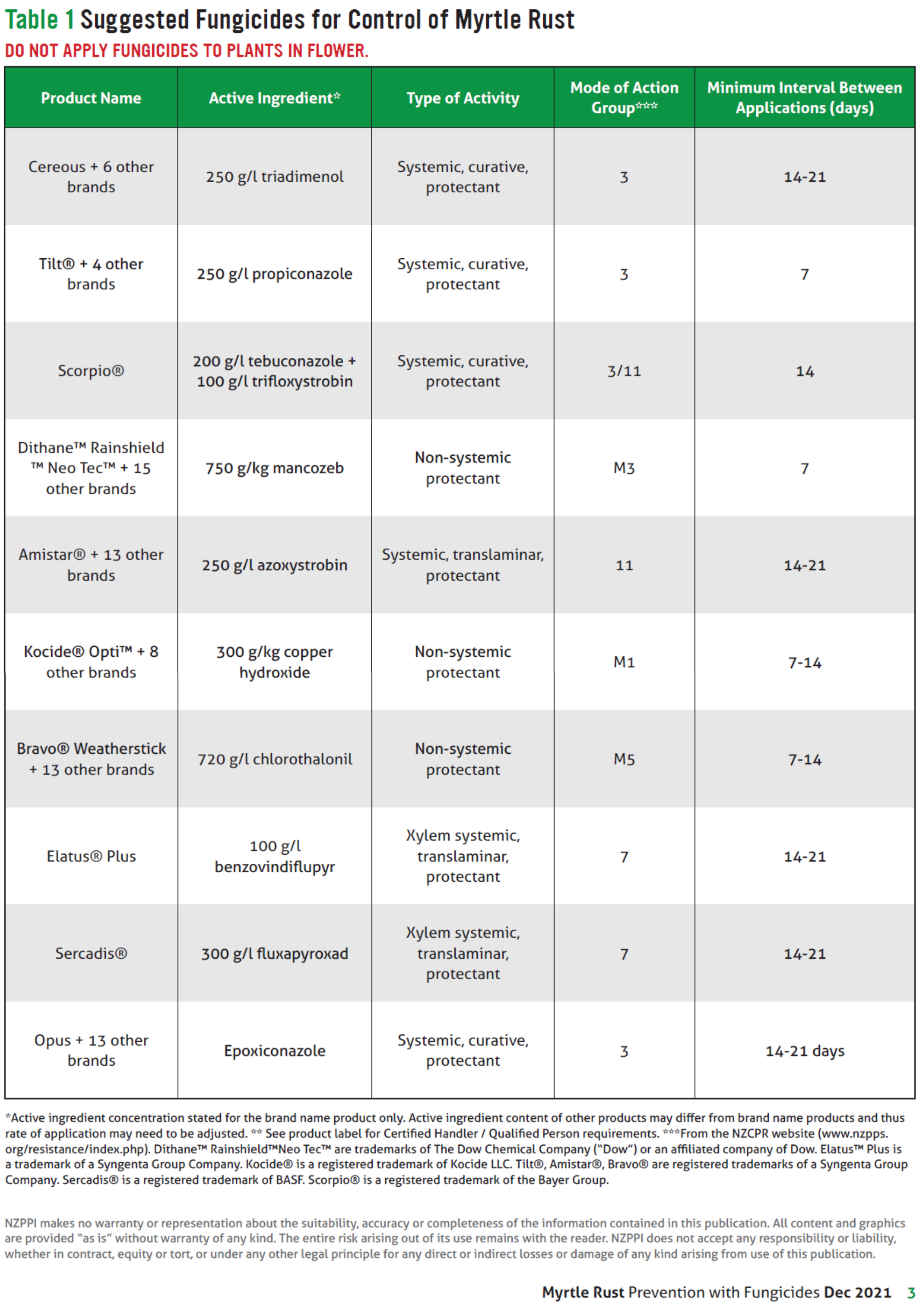


Table 1 Suggested Fungicides for Control of Myrtle Rust

DO NOT APPLY FUNGICIDES TO PLANTS IN FLOWER.

Product Name	Active Ingredient*	Type of Activity	Mode of Action Group***	Minimum Interval Between Applications (days)
Cereous + 6 other brands	250 g/l triadimenol	Systemic, curative, protectant	3	14-21
Tilt® + 4 other brands	250 g/l propiconazole	Systemic, curative, protectant	3	7
Scorpio®	200 g/l tebuconazole + 100 g/l trifloxystrobin	Systemic, curative, protectant	3/11	14
Dithane™ Rainshield ™ Neo Tec™ + 15 other brands	750 g/kg mancozeb	Non-systemic protectant	M3	7
Amistar® + 13 other brands	250 g/l azoxystrobin	Systemic, translaminar, protectant	11	14-21
Kocide® Opti™ + 8 other brands	300 g/kg copper hydroxide	Non-systemic protectant	M1	7-14
Bravo® Weatherstick + 13 other brands	720 g/l chlorothalonil	Non-systemic protectant	M5	7-14
Elatus® Plus	100 g/l benzovindiflupyr	Xylem systemic, translaminar, protectant	7	14-21
Sercadis®	300 g/l fluxapyroxad	Xylem systemic, translaminar, protectant	7	14-21
Opus + 13 other brands	Epoxiconazole	Systemic, curative, protectant	3	14-21 days

*Active ingredient concentration stated for the brand name product only. Active ingredient content of other products may differ from brand name products and thus rate of application may need to be adjusted. ** See product label for Certified Handler / Qualified Person requirements. ***From the NZCPR website (www.nzpps.org/resistance/index.php). Dithane™ Rainshield™Neo Tec™ are trademarks of The Dow Chemical Company ("Dow") or an affiliated company of Dow. Elatus™ Plus is a trademark of a Syngenta Group Company. Kocide® is a registered trademark of Kocide LLC. Tilt®, Amistar®, Bravo® are registered trademarks of a Syngenta Group Company. Sercadis® is a registered trademark of BASF. Scorpio® is a registered trademark of the Bayer Group.

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