Final Report

Development of regional disease risk models for fungal diseases of pyrethrum

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Project code:

PY20000

Project:

Development of regional disease risk models for fungal diseases of pyrethrum (PY20000)

Disclaimer:

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Contents

Public summary

Pyrethrum is grown in Tasmania and Victoria for the commercial production of pyrethrins, natural insecticidal compounds in the achenes of pyrethrum flower heads. Grower contracting, processing and export is conducted by Botanical Resources Australia (BRA), based in Ulverstone Tasmania. Australia is the major producer of pyrethrins, producing more than 50% of the world market. However, the industry's ability to consistently meet market production requirements is negatively impacted by several factors, most notably fungal diseases. The diseases ray blight and tan spot, both caused by fungal pathogens, are the major diseases impacting pyrethrum production. Currently, a standard recommended spray program is deployed industry wide to manage these diseases. Managing these diseases represents significant financial and environmental costs to growers. Anecdotal evidence from growers and results obtained from previous studies suggests that different growing regions and/or seasons are subject to different levels of disease pressure. Thus, this project was developed in collaboration with the pyrethrum industry to investigate the environmental conditions that drive tan spot and ray blight outbreaks. Disease prediction was aimed to provide growers tools to make disease management decisions based on their specific crop conditions. This would ensure high risk crops are given adequate protection but allow reduction in fungicide inputs in low-risk crops and/or seasons.

Work undertaken in this project included a combination of field, greenhouse, and controlled environment studies. Field studies into the impact and the timing of that impact, of fungal diseases on pyrethrum yields were undertaken in collaboration with BRA across four seasons from 2020 to 2023. Field surveys were conducted on commercial properties across the 2021 and 2022 growing seasons with monitoring of fungal disease loads and environmental conditions. These surveys were supported with targeted greenhouse and controlled environment studies were conducted to supplement field observations. Conducting all work in direct collaboration with BRA and pyrethrum growers was to ensure visibility to, and feedback from, industry.

The findings of this project highlighted the different times during the season that tan spot and ray blight reduce crop yields. Yield losses from tan spot were associated with that disease occurring in late winter and early spring. Disease carryover from previous seasons and spring rainfall were the major drivers of tan spot in pyrethrum. Identified thresholds for cropping density and spring rainfall provide tools to the industry for determining the frequency and timing of fungicide applications to sustainably manage this disease moving forward.

Ray blight in spring and early summer also resulted in significant yield losses. As a result of these findings, the industry has already changed management strategy with the removal of the pre-existing flowering fungicide program and supplementation of the spring program recommendations to improve control of ray blight in the late spring period. Mild temperatures, regular occurrence of days with rainfall and high humidity, in conjunction with proximity to neighbouring crops were the major drivers of ray blight outbreaks. The number and timing of fungicides in the late spring period can further be refined based on the predictive factors identified in this project.

Keywords

Pyrethrum, fungal disease, foliar disease, predictive modelling, disease management, ray blight, tan spot, yield loss

Introduction

The Australian pyrethrum industry products over 50% of the world market of pyrethrins, which are natural insecticides. Pyrethrum cropping is headquartered in northern Tasmania, where the majority of crops are grown. Additional cropping is conducted in Victoria. All pyrethrum crops are under grower contract with Botanical Resources Australia (BRA), who then undertake industrial extraction of pyrethrins from harvested material. Pyrethrum yields are negatively impacted by a complex of fungal diseases that attack crops through winter, spring, and summer. This includes diseases such as anthracnose (Barimani et al. 2013), *Paraphoma* crown rot (Moslemi et al. 2016; Moslemi et al. 2018), *Sclerotinia* crown rot (Scott et al. 2014), winter blight, *Itersoniliia* blight (Pilkington et al. 2023), and *Botrytis* and *Sclerotinia* flower blight (Pethybridge et al. 2008c). However, evidence suggests that tan spot, caused by *Didymella tanaceti* (Pearce et al. 2016; Pethybridge et al. 2008b), and ray blight, caused by *Stagonosporopsis tanaceti* (Pethybridge and Wilson 1998; Vaghefi et al. 2012), are the most damaging pathogens in this complex (Scott and Pearce 2020).

To mitigate the impact of foliar diseases, a comprehensive prophylactic fungicide program is deployed with individual focuses on the winter, spring, and early summer periods (Pethybridge et al. 2005; Pethybridge et al. 2008a). However, there are environmental and financial costs associated with this program place. Additionally, long-term fungicide usage in horticultural crops is often resultant in fungicide resistance developing within pathogen populations, significantly reducing efficacy. Such occurrences have already been identified in pyrethrum crops. Evidence of resistance to carbendazim in *Botrytis cinerea* (O'Malley 2012) and boscalid in *D. tanaceti* (Pearce et al. 2019) have already necessitated the removal of these chemicals from the management program. Therefore, there is pressure on the industry to reduce this reliance on chemical fungicides, ideally while still minimising the risk of crop losses from disease.

Findings from Hort Innovation project PY16000 (Scott and Pearce 2020), highlighted the potential impact of environmental variability between pyrethrum cropping regions on foliar disease outbreaks. Previous work highlighted the importance of seed borne *S. tanaceti* in conjunction with high autumn rainfall to ray blight outbreaks (Pethybridge et al. 2011). However, at temporal shift in the relative abundance of this disease has now been observed with ray blight now observed later in the growing season (Hay et al. 2015a). Additionally, as tan spot has previously been a minor disease of pyrethrum, it has received little investigation regarding the epidemiological factors that drive outbreaks. Thus, (re)-evaluation of the epidemiological drivers of the most damaging foliar diseases is warranted. It is hypothesised that modifying the existing fungicide program in response to the specific environmental requirements for ray blight and tan spot outbreaks provides an opportunity to reduce fungicide applications in low-risk regions whilst maintaining crop yields in high-risk regions. Coupled with weather forecasts, such programs may be further adapted to account for low- and high-risk cropping seasons.

This project aimed to evaluate i) the environmental conditions that promote the occurrence of tan spot and/or ray blight in pyrethrum; and ii) the timing of impact of ray blight and tan spot outbreaks on pyrethrum yield. These factors were then combined to provide the industry predictive mechanisms for the deployment of targeted chemical fungicide strategies to control these diseases based on field location and climatic conditions.

Methodology

1. Relationships between disease pressure and yield loss

The relationship between pathogen incidence and pyrethrum crop yield loss was examined across four seasons: 2020/21, 2021/22, 2022/23 and 2023/24. A series of fungicide spray trials conducted in collaboration with BRA as part of the industry's evaluations of potential fungicide products pathogen load and crop yield were assessed. Individual trials were conducted in either the autumn (2 sites), winter (8 sites), mid-spring (11 sites) or early summer (10 sites) periods within commercial pyrethrum fields across northern Tasmania. At each site, fungicide treatments were used to create varying pathogen loads. Following fungicide treatment, pathogen incidence was estimated as per research area 2. Following pathogen incidence measurement all trial plots were subject to standard industry disease management until harvest. Crop yields were estimated for individual plots in the following January. Additional data obtained in Hort Innovation project PY16000 was also incorporated from seasons 2017/18 (autumn: 2 sites; winter: 2 sites), 2018/19 (winter: 2 sites), and 2019/20 (autumn: (1 site). Relationships between disease parameters and final crop yield were then modelled to estimate the impact, and the timing of that impact, on final crop yield.

2. Regional differences in pyrethrum diseases

Regional differences in tan spot and ray blight incidence were monitored from winter to early summer in each of 2021 and 2022. Twenty-one first harvest fields in 2021 and 20 in 2022 spread across the typical pyrethrum production areas in Tasmania and Victoria were monitored monthly for the incidence of foliar fungal pathogens (Hay et al. 2015b). In all fields no fungicide spray strips were established for monitoring from August to December each season. Sites were monitored monthly for fungal pathogens with an emphasis on the causal agents of tan spot and ray blight. Estimates of weather conditions for individual sites will be obtained from the SILO database (https://www.longpaddock.qld.gov.au/silo/). Historical weather conditions across the pyrethrum cropping regions were used to define specific cropping regions. Monitored sites were then analysed for differences based on defined region. In addition to regional monitoring, intensive monitoring at six sites each season pathogen loads were monitored using a combination of trap plants and rotorod spore traps. Samples were collected at weekly intervals from August to December each season. Weather monitoring at each site was used to establish relationships with climatic conditions and patterns in pathogen inoculum load.

3. Disease outbreak prediction

Data obtained under research areas 1 and 2 were combined to develop disease risk models for the outbreak of tan spot and ray blight epidemics. Laboratory experiments were conducted to examine the conditions that favour spore formation, spore germination, leaf infection and host colonization by *Didymella tanaceti* and *Stagonosporopsis tanaceti,* the causal agents of tan spot and ray blight, respectively. Key environmental parameters examined included temperature and light. Initial experiments examined the growth rate and pycnidial formation of each pathogen in plate culture. Subsequent experiments evaluated the optimal temperature and light conditions for the infection lifecycle of each pathogen in plants using controlled environment growth chambers. These were incorporated to predict the rate of spore formation following infection under varying temperatures. Observations from the intensively monitored sites were then used to develop decision tree models for the occurrence of tan spot and ray blight infection events. These models were combined with observations across all sites monitored during this project, and data collected from 59 sites from 2019 to 2020 as part of Hort Innovation project PY16000, to produce predictions of the risk of tan spot and/or ray blight epidemics during the key crop development periods identified in research area 1 for each disease. Pathogen incidence levels were converted to risk categories based on predicted yield losses (low < 5%; moderate 5-20%; high > 20%) prior to final decision tree modeling to provide a framework for industry disease management decisions.

4. Industry collaboration and engagement

Annual meetings with the Pyrethrum Growers committee and BRA representatives, which formed the project reference group, were held to oversee the conduct of this project. All field research trials were conducted in collaboration with BRA in commercial pyrethrum paddocks. Direct collaboration with industry growers, agronomists and research staff facilitated ready communication of project aims and outcomes. Annual pyrethrum disease forums held in July 2022 and 2023 for pyrethrum researchers, BRA research staff and BRA agronomists provided an additional avenue for dissemination and discussion of project findings.

Results and discussion

1. Relationships between disease pressure and yield loss

Estimates of the impact of foliar fungal pathogens were divided into four time points coinciding with current management programs in commercial pyrethrum production: 1) autumn, prior to winter fungicide application; 2) late winter, post-winter fungicides; 3) mid-spring, post-early spring fungicide applications; and 4) early summer, post-late spring fungicides.

In autumn, the pathogens of tan spot, ray blight, winter blight., pink spot, anthraconose and *Itersonilia* blight were recorded across seasons and sites. However, only the tan spot and ray blight pathogens were observed at moderate (>20%) incidences in the majority of crops. Pathogen incidence in autumn was not observed to have any significant negative relationship with crop yield in summer.

The same set of six foliar pathogens were observed in all trial sites in late winter. Of these, tan spot was the dominant pathogen, with incidences at greater than 10% in all fields, and higher than 50% in 6 of 12 fields. Modelling indicated that only tan spot incidence had a significant negative effect on pyrethrum yield. A tan spot incidence of 100% during August resulted in predicted losses of 13.7% final crop yield.

During mid-spring, both tan spot and ray blight were observed to significantly impact on pyrethrum yield. While the *Itersonilia* blight and anthracnose pathogens were also recorded in all fields, these were not significant predictors of yield loss. Modeled estimates indicated that at incidences of 100%, tan spot and ray blight were responsible for 72 and 54% yield losses respectively. However, ray blight (range = 0 to 60%) to was also recorded at a lower range of incidences than tan spot (range = 0 to 96%) in this period. This suggests that tan spot presents the greater risk to yield during this period than ray blight.

In early summer, the ray blight, tan spot, winter blight, *Botrytis* flower blight and *Itersonilia* blight pathogens were detected in developing flowers. Of these, only ray blight was estimated to have a statistically significant impact on pyrethrum yield. It was estimated that a 50% yield loss would occur when ray blight was present in 100% of pyrethrum plants.

Overall, this highlights the extent in timing at which ray blight and tan spot negatively impact pyrethrum production. It suggests that tan spot infection damages pyrethrum yields during the late winter and, especially, the early spring periods in the growing season. At this time, pyrethrum goes through rapid increases in green leaf area. However, ray blight impacts crop yields later in the season; reducing crop yields during the early and late spring periods, which coincides with pyrethrum bud development and maturation (Pethybridge et al. 2013). As the tan spot and ray blight pathogens are known to have differential responses to fungicides (Pearce et al. 2019; Scott et al. 2015), there exists an opportunity for growers to deploy fungicide products at different time points in the growing season targeting tan spot and ray blight specifically.

2. Regional differences in pyrethrum diseases

Based on climatic data from 2018 to 2022, six clusters of cropping districts were identified. Out of these, one spatially non-contiguous region was formed and as such, the Wynyard district was defined as its own growing region distinct from the east Devonport region. Similarly, an 8th growing region comprising of Pipers Brook and Scottsdale was differentiated from East Devonport for the same reason. Of these eight growing regions, field samples were available from six during 2021 and 2022.

Across seasons in spring, tan spot was the dominant disease detected. In August, mean regional incidence of tan spot varied between 14 and 29% of plants; while in October, it varied between 31 and 63%. In early summer, ray blight was the dominant disease with regional mean incidences varying between 5 and 66%. *Botrytis* flower blight, *Itersonilia* blight, anthracnose and winter blight were also detected at varying frequencies during sampling. While sporadic differences in disease incidence were detected between regions for individual months during this study, these were not consistent between seasons. Similarly, when data was combined across months no statistically significant differences between regions were observed for the major pathogens. As such, it was concluded that geographic region alone, as defined in this study, could be used as reliable predictor of fungal disease pressure in pyrethrum cropping.

3. Disease outbreak prediction

Outbreaks of tan spot

Based on observed relationships between tan spot incidence and yield loss (research area 1 above), two key periods were considered in outbreak modelling: 1) late winter (August) and 2) spring (September to November).

Tan spot incidence in August, prior to the initiation of the commercial spring fungicide program, was found to be determined by the cropping density surrounding a given field (Fig. 1). The area of crop harvested the previous summer within 5 km of an individual monitoring site was the strongest determinant of tan spot incidence. When less than 34 ha of crop were within 5 km, mean incidence in August was 8.9% of plants. However, when that area was greater than 34 ha mean incidence was 28%. All fields that were characterized as moderate risk of yield loss in August had greater than 34 ha within 5 km. No high risk sites were observed in August during this project. That the crop area from the previous season was a higher predictor than crop area in the current season indicates that tan spot carryover from one season from older to newer crops is a significant constraint on pyrethrum production.

During the spring period, prior tan spot incidence within a crop and rainfall were the ultimate drivers of tan spot outbreaks. When modelled across 98 fields between 2019 and 2022, if rainfall in the previous four weeks was less than 38.7 mm mean tan spot incidence in October was 2.4%. However, when it was greater than 38.7 mm, mean incidence was 57%. Extrapolating to risk of yield loss; all low risk sites received less than 38.7 mm rainfall, and all moderate and high risk sites received greater than 38.7 mm rainfall in that four week period (Fig. 1). Across the spring period (September to November), when data on tan spot the previous month was available (2021 and 2022 only), this parameter was modelled as the major driver of tan spot incidence in a given month.

Ulitmately, this work has shown that carryover of inoculum from previous crops and rainfall are the key drivers of tan spot outbreaks. The action thresholds identified in this project provide a guide for intensity of management by growers. Crops sown in high density cropping regions should be considered for higher management strategies in winter to minimize August and subsequent spring tan spot incidences. Similarly, monthly rainfalls of ~40 mm or higher during spring could be treated as triggers for fungicide application.

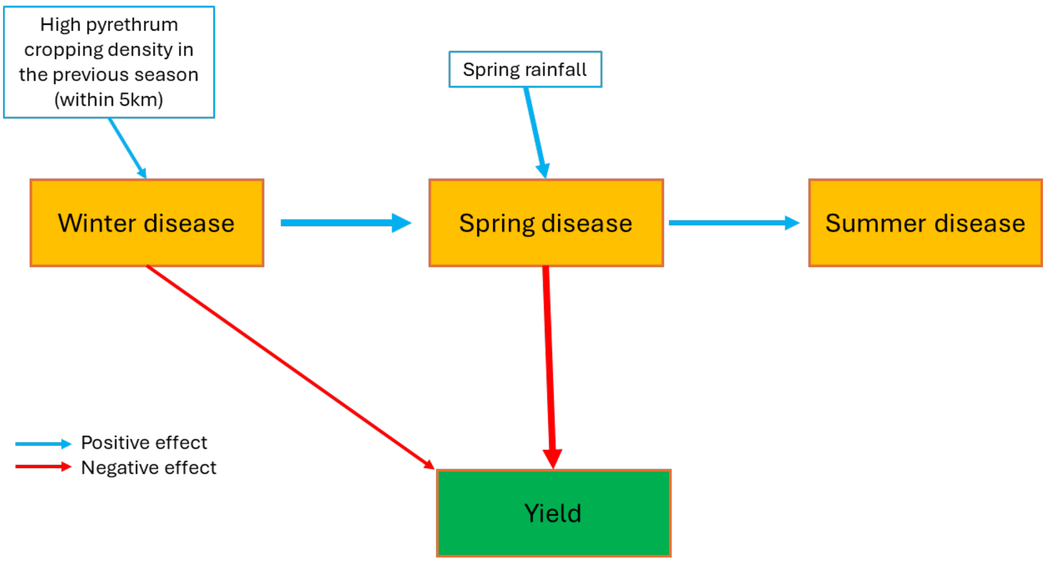

Fig. 1 Schematic of the interactions between environmental factors, tan spot incidence in pyrethrum and crop yield. Blue arrows indicate a positive effect leading to an increase in the response factor. Red arrows indicate a negative effect on the response factor. The width of arrows is indicative of strength of effect but is not to scale.

Outbreaks of ray blight

Based on observed relationships between ray blight incidence and yield loss (research area 1 above), two key periods were considered in outbreak modelling: 1) spring (September to November) and 2) summer (December).

While ray blight incidence in August was not observed to negatively impact final crop yield, it was a significant driver of subsequent ray blight incidence in spring coupled with the occurrence of high relative humidity days (min. humidity >80%). Initial ray blight incidence in August was determined by proximity to neighbouring pyrethrum fields (Fig. 2). When the distance to the nearest pyrethrum crop was greater than 0.94 km, mean ray blight incidence was 4.8%. However, when the nearest crop was closer than 0.94 km mean incidence was 25%.

When prior ray blight incidence was unknown, spring incidence was predicted by a risk parameter (STinf.w) developed by modelling rate of trap plant infection at intensively monitored sites in 2021 and 2022. STinf.w combined rain days (>1 mm), high relative humidity days and pathogen growth rate based on temperature. In October across fields in 2019 to 2022, when STinf.w was less than 0.296 40 of 43 fields were low risk of yield loss from ray blight. When STinf.w was higher 29 of 55 fields were moderate or high risk. Additionally, if the nearest pyrethrum crop within 0.26 km 12 of 12 crops were classified as moderate or high risk of yield loss.

Ray blight incidence in early summer, was best predicted by the parameter STinf.w alone. When cumulative STinf.w over the previous four weeks was greater than 0.271, 14 of 18 fields were moderate or high risk of yield losses from ray blight. Conversely when parameter estimates were less than this, 19 of 22 fields were low risk of yield loss.

The observed relationships between prior disease load, rainfall and temperature, and ray blight incidence are consistent with historical findings (Pethybridge et al. 2011). During the key periods of October and November, the infection risk parameter, STinf.w, could be used to guide growers as to the timing and frequency of fungicide applications to minimize yield losses.

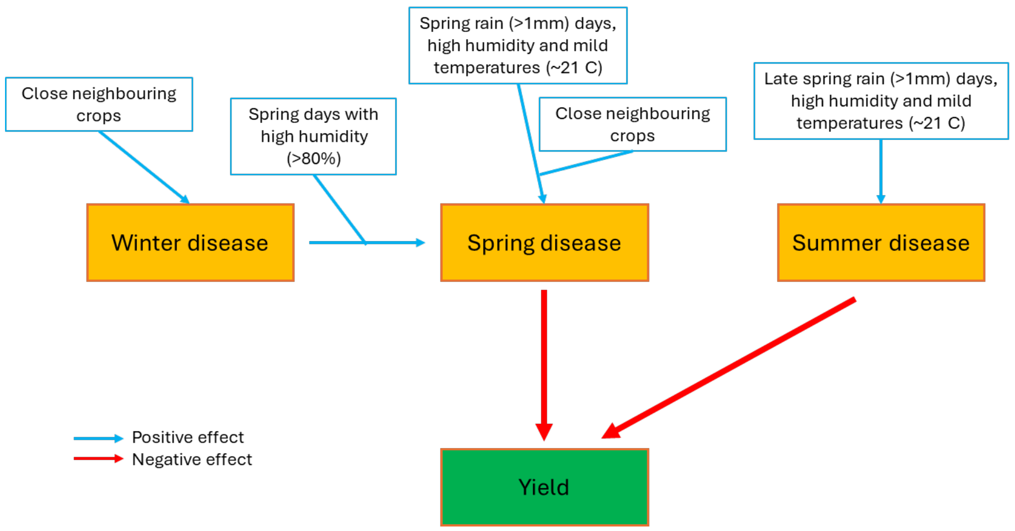

Fig. 2 Schematic of the interactions between environmental factors, ray blight incidence in pyrethrum and crop yield. Blue arrows indicate a positive effect leading to an increase in the response factor. Red arrows indicate a negative effect on the response factor. The width of arrows is indicative of strength of effect but is not to scale.

Outputs

Table 1. Output summary

Output	Description	Detail
Predictive model for tan spot	A predictive model, incorporating climatic and cropping density data was developed for the prediction of severity of tan spot outbreaks and their impact on pyrethrum yields. This model aimed for industry deployment in commercial operation to support and improve management of this disease.	Details of the predictive model are included in this report. Adoption of model by industry is dependent upon validation under commercial operations. Conversations with BRA regarding model validation are ongoing with an aim to progress in 2024. Ultimate deployment of the model is the responsibility of BRA as the commercial entity that manages the pyrethrum industry in Australia.
Predictive model for ray blight	A predictive model, incorporating climatic data and proximity to neighbouring crops was developed for the prediction of severity of ray blight outbreaks and their impact on pyrethrum yields. This model aimed for industry deployment in commercial operation to support and improve management of this disease.	Details of the predictive model are included in this report. Adoption of model by industry is dependent upon validation under commercial operations. Conversations with BRA regarding model validation are ongoing with an aim to progress in 2024. Ultimate deployment of the model is the responsibility of BRA as the commercial entity that manages the pyrethrum industry in Australia.
Protocol for measuring airborne spore load of tan spot and ray blight	A spore trapping protocol for the detection of airborne spores using a combination of rotorod impaction spore traps and real time PCR quantification. Protocol provides a tool for industry researchers for the monitoring of pathogen movement between crops over time.	This protocol has been described in the appendices of this report. This protocol in part provides the basis for a new research project supported by BRA and the Department of Natural Resources and Environment's Agricultural Development Fund (listed here): https://nre.tas.gov.au/agriculture/government-and-community-programs/agricultural-development-fund
Article on *Itersonilia* blight	Scientific publication in the international journal Plant Disease. Article outlines the disease *Itersonilia* blight caused by *Itersonilia perplexans.*	Copy of article provided directly to BRA and included as an appendix to this report. Article is publicly available at: https://apsjournals.apsnet.org/doi/full/10.1094/PDIS-11-22-2604-PDN

Research presentations to industry disease research forums	Presentation of the findings of this project were conducted in each of 2022, 2023 and 2024. In attendance at these meetings were researchers working in pyrethrum disease research and BRA agronomists.	Presentation slides were provided to BRA for internal dissemination. Copies of the presentations are included as an appendix to this report.

Outcomes

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Improved understanding of the epidemiology of tan spot and ray blight with specific reference to the environmental conditions that favour outbreaks	Sustainable management of disease in pyrethrum • Understanding relationships between environmental and disease outbreaks provides tools for strategic management of disease in a more sustainable manner.	The impact of environment on tan spot had not been conducted prior to this project. As such all knowledge generated was novel to the industry. The industry's understanding of the impact of climate on ray blight was refined to incorporate a predictive parameter for outbreaks during spring and summer. This re-enforced and built upon work conducted over 10 years ago. In both instances, this new knowledge provided a basis for the development of predictive models for these diseases as outlined below.	These findings were communicated directly to 100% of BRA field agronomists in June 2024.
A greater understanding of the impact of foliar disease on pyrethrum yield	Sustainable management of disease in pyrethrum • Understanding the timing and extent of foliar pathogens facilitates the development of tools decisions for the deployment of management strategies	The extent and timing of tan spot impact on crop yields was unknown with no direct studies conducted prior to the commencement of this project. Thus, knowledge generated in this project has greatly increased understanding. Ray blight and its impact has previously been studied. However, knowledge of its impact on yield predates the emergence of tan spot. Thus, this understanding has been updated to incorporate current disease constraints. This new knowledge provides a basis for strategic deployment of	Feedback from BRA indicates that these findings align with anecdotal evidence from agronomists and field staff. These findings were communicated directly to 100% of BRA field agronomists in June 2024.

		disease management strategies by the industry	
Adoption of regional/seasonal specific disease management protocols	Sustainable management of disease in pyrethrum • Development of predictive tools to allow identification of low- and high-risk scenarios as tools for strategic deployment of disease management protocols • Improved disease management protocols deployment for more sustainable and effective management of ray blight	Feedback from the industry is that they see the decision thresholds for disease management identified in this project as actionable. Initial conversations are underway to support the industry in conducting commercial validation of these in the 2024 season. In 2023, standard industry grower recommendations were 4 to 5 spring fungicide applications and no summer applications to flowers. This modification to commercial recommendations was a direct response to findings in this project.	These findings were communicated directly to 100% of BRA field agronomists in June 2024. This outcome has been realized by deployment of a modified disease management strategy recommendation. This strategy is recommended to all pyrethrum growers by BRA agronomists.

Monitoring and evaluation

Table 3. Key Evaluation Questions

Key Evaluation Question	Project performance	Continuous improvement opportunities
To what extent has the project provided strategies for increasing the medium- and long-term efficacy of disease management within the industry?	This project provided two mechanisms for increasing the medium- and long-term efficacy of disease management. Firstly, it was identified that late spring ray blight detrimentally impacts crop yields. Previous findings that the impact of *Botyrtis* flower blight is minimal, which was supported by findings in this project. Thus, the industry has now adopted a revised management strategy directly incorporating this information as part of recommendations to growers. Secondly, the predictive models developed have provided tools for identifying low- and high-risk cropping sites. This can be used to reduce fungicides in low-risk sites and thus reduce the risk of industry wide management failures in the future.	The co-design structure and direct industry collaboration of this project ensured that this project met this Key Evaluation Question. It would be recommended that this model continue in future such collaborations.
To what extent has the project addressed the disease management issues faced by the industry?	This project directly addressed the management of the diseases tan spot and ray blight of pyrethrum. Examination of the timing of outbreaks of these diseases and the ultimate impact on crop yields highlighted the differences between these diseases. These differences provide growers with opportunities for more specific control strategies for the individual diseases. Predictive modelling of tan spot and ray blight outbreaks was undertaken to identify low- and high-risk diseases scenarios. The decision thresholds identified provide the industry with tools for strategic deployment of fungicide applications for more effective disease management.	The scope of this project enabled the development of predictive models for the pyrethrum industry. However, insufficient time and resources were available for commercial validation of the findings. This is a failing that needs to be incorporated in future studies of this nature.
Have project outcomes been effectively disseminated to the industry partner and/or levy payers via: • Regular project meetings? • Engagement events? • Field staff network? • Written reports?	Project findings and outcomes were disseminated to BRA research staff, agronomists and growers through the following mechanisms: 1. Formal co-design meetings between BRA and project staff were conducted approximately 6-monthly with additional meetings held as needed. Over the 3.5 years	The pyrethrum industry has previously published a regular newsletter to growers. Publication of this became irregular during this project. Regular publication of short research summaries tailored to growers would provide another avenue for dissemination and should be considered in future

	of this project, 11 formal meetings was combined with frequent informal communications. 2. Pyrethrum disease forums were held by BRA annually from 2022 to 2024. Research findings were presented and discussed at each of these meetings. All BRA research and agronomist staff were present at these forums. 3. Research communications, both formal and informal, were held growers and agronomists through pyrethrum field tours held in 2021 and 2022. Additionally, the TIA Forthside Field Day held annually in November/December provided project staff the opportunity to converse with industry members in each of 2021, 2022 and 2023.	projects.
What efforts did the project make to improve structure and design of studies and analysis whilst maintaining scientific rigour?	Project implementation and co-design was conducted in collaboration with BRA throughout the life of the project. Through this collaboration, TIA staff were focused on ensuring that scientific rigour was maintained while BRA staff were focused on ensuring the practicality and relevance of research to the industry. Two key changes to the planned work were made on this basis: 1. The initial number of survey sites planned was reduced to a targeted 20 per season, while increasing the frequency of surveys to monthly. 2. Greenhouse studies into fungal impact on yield were abandoned in favour of increased field studies. Initial greenhouse studies produced results of questionable relevance. Thus, greater emphasis was placed on the more reliable and relevant field data.	Co-design with views towards practicality and scientific rigour served this project well. Ensuring that research planning remains dynamic during a project and not rigid to initial design is an important consideration into the future. This will ensure that project activities are responsive to findings and continued industry relevance.

Recommendations

Based on the findings of this project the following recommendations are made:

1. Conduct commercial validation tan spot and ray blight predictive models

The predictive models developed in this project were conducted in commercial farms, but under research trial conditions. It is thus recommended that the pyrethrum industry undertake commercial validation of these models in conjunction with varying disease management strategies in accordance with predictions. If successful, this work would be the last step to widescale commercial adoption of these models for optimizing management of ray blight and tan spot.

2. Development of routine disease testing protocols for commercial deployment

This project highlighted the importance of knowing the pathogen load present within commercial crops. Carryover from previous season crops, and in crop buildup of inoculum were key drivers of tan spot outbreaks. Similarly, close proximity to infected crops, and in crop buildup of inoculum were drivers of ray blight in spring. Routine testing for inoculum loads within crops for both of these diseases would provide earlier identification of high-risk sites and supplement predictions of disease outbreaks based on weather forecasts.

3. Develop pyrethrum crops with a 12 month or less cropping cycle

Carryover of tan spot inoculum from one season to the next appears to be a major failing of the current cropping system. Pyrethrum is currently in the ground for a period of 15-18 months prior to harvest. Thus, no cropping break is present allowing easy transmission of tan spot from older crops to newly established ones. Efforts to shorten pyrethrums cropping cycle and provide a break between seasons would thus limit this transmission and reduce tan spot outbreaks.

Refereed scientific publications

Journal article

Pilkington, S., Scott, J., Pearce, T., Tan, Y. P., and Hay, F. 2023. Confirmation of *Itersonilia perplexans* infecting pyrethrum (*Tanacetum cinerariifolium*) in Australia. Plant Dis. 107:2258.

References

1 Barimani, M., Pethybridge, S. J., Vaghefi, N., Hay, F. S., and Taylor, P. W. J. 2013. A new anthracnose disease of pyrethrum caused by *Colletotrichum tanaceti* sp nov. Plant Pathol. 62:1248-1257.

2 Hay, F. S., Gent, D. H., Pilkington, S. J., Pearce, T. L., Scott, J. B., and Pethybridge, S. J. 2015a. Changes in distribution and frequency of fungi associated with a foliar disease complex of pyrethrum in Australia. Plant Dis. 99:1227-1235.

3 Hay, F. S., Gent, D. H., Pilkington, S., Pearce, T. L., Scott, J. B., and Pethybridge, S. J. 2015b. Changes in distribution and frequency of fungi associated with a foliar disease complex of pyrethrum in Australia. Plant Dis. 99:1227-1335.

4 Moslemi, A., Ades, P. K., Groom, T., Crous, P. W., Nicolas, M. E., and Taylor, P. W. J. 2016. Paraphoma crown rot of pyrethrum (*Tanacetum cinerariifolium*). Plant Dis. 100:2363-2369.

5 Moslemi, A., Ades, P. K., Crous, P. W., Groom, T., Scott, J. B., Nicolas, M. E., and Taylor, P. W. J. 2018. Paraphoma chlamydocopiosa sp. nov. and Paraphoma pye sp. nov., two new species associated with leaf and crown infection of pyrethrum. Plant Pathol. 67:124-135.

6 O'Malley, T. B. 2012. Epidemiology and management of flower diseases of pyrethrum. PhD, School of Agricultural Science, University of Tasmania Burnie, Tasmania, Australia.

7 Pearce, T. L., Wilson, C. R., Gent, D. H., and Scott, J. B. 2019. Multiple mutations across the succinate dehydrogenase gene complex are associated with boscalid resistance in *Didymella tanaceti* in pyrethrum. PLoS ONE 14:e0218569.

8 Pearce, T. L., Scott, J. B., Crous, P. W., Pethybridge, S. J., and Hay, F. S. 2016. Tan spot of pyrethrum is caused by a *Didymella* species complex. Plant Pathol. 65:1170-84.

9 Pethybridge, S. J., and Wilson, C. R. 1998. Confirmation of ray blight disease of pyrethrum in Australia. Austral. Plant Pathol. 27:45-48.

10 Pethybridge, S. J., Gent, D. H., and Hay, F. S. 2011. Epidemics of ray blight on pyrethrum are linked to seed contamination and overwintering inoculum of *Phoma ligulicola* var. *inoxydabilis*. Phytopathology 101:1112-1121.

11 Pethybridge, S. J., Hay, F. S., Wilson, C. R., and Groom, T. 2005. Development of a fungicide-based management strategy for foliar disease caused by *Phoma ligulicola* in Tasmanian pyrethrum fields. Plant Dis. 89:1114-1120.

12 Pethybridge, S. J., Hay, F. S., Groom, T., and Wilson, C. R. 2008a. Improving fungicide-based management of ray blight disease in Tasmanian pyrethrum fields. Plant Dis. 92:887-895.

13 Pethybridge, S. J., Gent, D. H., Groom, T., and Hay, F. 2013. Minimizing crop damage through understanding relationships between pyrethrum phenology and ray blight disease severity. Plant Dis. 97:1431-1437.

14 Pethybridge, S. J., Jones, S. J., Shivas, R. G., Hay, F. S., Wilson, C. R., and Groom, T. 2008b. Tan spot: a new disease of pyrethrum caused by *Microsphaeropsis tanaceti* sp. nov. Plant Pathol. 57:1058-1065.

15 Pethybridge, S. J., Hay, F. S., Esker, P. D., Gent, D. H., Wilson, C. R., Groom, T., and Nutter, F. W. 2008c. Diseases of pyrethrum in Tasmania: challenges and prospects for management. Plant Dis. 92:1260-1272.

16 Pilkington, S., Scott, J., Pearce, T., Tan, Y. P., and Hay, F. 2023. Confirmation of *Itersonilia perplexans* infecting pyrethrum (*Tanacetum cinerariifolium*) in Australia. Plant Dis. 107:2258.

17 Scott, J. B., and Pearce, T. L. 2020. Final report for PY16000: Integrated Disease Management in Pyrethrum: Horticulture Innovation Australia Ltd.

18 Scott, J. B., Gent, D. H., Pethybridge, S. J., Groom, T., and Hay, F. S. 2014. Crop damage from Sclerotinia crown rot and risk factors in pyrethrum. Plant Dis. 98:103-111.

19 Scott, J. B., Pearce, T. L., Pilkington, S., Hay, F. S., and Wilson, C. R. 2015. Genetics governing the differential response to boscalid of Microsphaeropsis tanaceti and Stagonosporopsis tanaceti. Phytopathology 105:S4.125.

20 Vaghefi, N., Pethybridge, S. J., Ford, R., Nicolas, M. E., Crous, P. W., and Taylor, P. W. J. 2012. *Stagonosporopsis* spp. associated with ray blight disease of Asteraceae. Austral. Plant Pathol. 41:675-686.

Intellectual property

No project IP or commercialisation to report.

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