Timing of Triazole-Based Spray Schedules for Managing Mungbean Powdery Mildew in Australia: a Meta-Analysis

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Abstract

Powdery mildew (PM), caused by two fungal species, *Podosphaera xanthii* and *Erysiphe vignae*, is a yield limiting foliar disease commonly found in mungbean (*Vigna radiata)* cropping areas of eastern region of Australia. Effective control of the disease relies largely on fungicide applications, mainly of the triazole group. Uncertainty in the current fungicide spray schedule recommendations, which advise commencing with a spray at the first signs of PM, prompted this study to evaluate PM severity and crop yield data obtained from fungicide trials which also tested spray schedules starting before (*early*) or after (*late*) first signs, applied singly or combined with a follow-up spray. A meta-analytic approach was employed to obtain mean differences of the PM severity and crop yield between plots sprayed with specific triazole-based spray schedules and nontreated plots. From 26 trials, 14 and 15 met the criteria for inclusion in the respective PM severity and yield analyses. The schedule with the first spray starting at first sign, with a follow-up spray 14 days later, resulted in significantly lower disease severity compared to all other schedules. However, the yield protected was only numerically higher and not statistically different compared to: single-spray at first sign, single-spray *late* or two-spray starting *late*. PM severity and yield in the *early* sprayed plots did not differ from the nontreated plots. These findings support the current recommendations and provide additional evidence that yields are still protected when delaying the first spray up to a week after disease onset. They also suggest that additional sprays may not always be necessary, thus reducing direct fungicide costs, indirect costs due to fungicide insensitivity and potential adverse effects to the environment.

Keywords: *Podosphaera xanthii*, *Erysiphe polygoni* , *Erysiphe vignae*, *Vigna radiata*, demethylase inhibitors, network meta-analysis

Introduction

Mungbean [*Vigna radiata* (L.) Wilczek] is a pulse crop primarily grown in Southeast Asia for human consumption either as raw pods, grain or added to meals after sprouting as an affordable source of protein (Lambrides and Godwin 2007). The dried grain can also be ground into a protein-enriched flour for uses in noodles, biscuits and cakes (Chankaew et al. 2013). Even though mungbean was first brought to Australia in the 1930s for use as a forage or green manure crop, it is still considered a relatively new commercial crop. In 2011, a cost-benefit analysis valued the return on investment for mungbean research at 18:1 (Australian Mungbean Association n.d.). Since then, high value export markets and new varieties with improved yields have increased profitability and the crop has been more widely adopted. Between 35 and 86.4 thousand hectares of dried beans are now planted annually in Australia (Clarry 2016). Nowadays, mungbean is grown as a short season summer legume crop predominantly within southern Queensland and northern New South Wales, this is the same region for which trials in this meta-analysis were undertaken. In 2019, approximately 90% of Australian mungbean was grown for export which received attractive returns of up to $1300 AUD per tonne (Queensland Government 2019).

Mungbean potentially yields up to 3 t/ha (Thomas et al. 2004) but the average Australian farm yields less than 1 t/ha (Chauhan and Williams 2018) with significant temporal and spatial variability, suggesting the urgent need for research efforts targeting production constraints. Abiotic constraints, insects and competition from weeds contribute to mungbean yield losses, in addition to the occurrence of diseases caused by fungi, bacteria and phytoplasmas (Wood and Easdown 1990; Conde and Diatloff 1991; Thakur and Agrawal 1995; Fuhlbohm et al. 1996, 2013; Wilson et al. 2001; Noble et al. 2019)

Among the fungal mungbean diseases in Australia, powdery mildew (PM), caused by obligate biotroph fungi *Podosphaera xanthii* (syn. *Podosphaera fusca* and *Erysiphe polygoni*) and *Erysiphe vignae* (Kelly et al. 2021), can reduce yield by 40% in susceptible cultivars grown under disease-conducive conditions (Lambrides and Godwin 2007). To date, ascospores produced in chasmothecia (sexual stage) have not been reported in Australia; hence the asexual airborne conidial spores that are produced abundantly on live hosts and dispersed by wind currents, are considered the primary inoculum for epidemics, while the alternate host or hosts remain unknown. Conditions for infection by PM pathogens are optimal when temperatures range between 22 °C and 26 °C (Pérez-García et al. 2009; Kelly et al. 2017). Powdery mildew is a polycyclic disease that develops quickly; the time from conidial germination to newly producing conidiophores disseminating conidia (a monocycle) can be as short as five days (Sparks and Kelly 2017). The characteristic white powdery fungal growth on the infected leaves negatively affects photosynthesis, leading to reduced yield quantity and quality (Pérez-García et al. 2009). In severe cases leaves become chlorotic, which can lead to premature leaf senescence.

Powdery mildew management involves the integration of cultural, genetic and chemical practices (Pandey et al. 2018; Sparks and Kelly 2017). In southern Queensland and northern New South Wales, sowing of mungbean crops is recommended between late spring (November) and mid-summer (January) to avoid the cooler autumn temperatures, which favor the disease (Australian Mungbean Association n.d.). While loci conferring quantitative resistance to PM in mungbean have been incorporated in mungbean breeding lines (Humphry et al. 2003; Zhang et al. 2008; Pandey et al. 2018; Douglas 2008); ongoing breeding efforts in Australia have focused on resistance to bacterial diseases given the feasibility to use fungicides for PM control. The recently released Opal-AU cultivar is rated as moderately susceptible (MS) to moderately resistant (MR) and is considered to contain the best resistance to PM (Douglas and McIntosh 2020) followed by Jade-AU (MS) and Green Diamond (Australian Mungbean Association n.d.). Losses up to 32.7% have been recorded in Jade-AU (Thompson 2016). However, cultivar resistance alone is not sufficient to control PM, hence fungicide applications are necessary when conditions for the disease are conducive.

Field trials conducted in eastern Australia over the past ten years have evaluated fungicide efficacy with a range of active ingredients and spray timings. The trial results are available only as gray literature, such as online trial reports (Kelly et al. 2017; Thompson 2016; Northern Growers Alliance 2013a, 2013b, 2013c, 2013d). In general, the best control of PM for yield protection has been achieved with a first application at the first signs, with a follow-up application two weeks later if conditions are favorable for disease development (Sparks and Kelly 2017; Thompson 2016). However, these results have been inconsistent, possibly due to environmental or trial-specific conditions as well as lack of statistical power in individual trials. Additionally, a fair comparison among several treatment options was not possible due to different combinations of treatment settings between the trials, such as fungicide active ingredient, number of sprays and spray timing. These issues can be dealt with by combining results from the primary studies to obtain estimates of both the size and uncertainty of the treatment effects via a systematic review with meta-analysis (MA). The method has become standard in plant pathology for summarizing data from uniform fungicide trials. Typically, MA models are fitted separately to data for each treatment against a control group (Madden and Paul 2011). Alternatively, a single model can be fitted in the form of a network of treatments where both direct and indirect evidence is used in the calculation of treatment effect sizes. The latter approach is called a network meta-analysis, one of the several meta-analytic methods that has found use for multiple treatment comparisons in plant disease management due to its estimates being considered more precise in some contexts (Madden et al. 2016).

The recently launched mobile app '*PowderyMildewMBM*' (Department of Primary Industries and Regional Development 2019) is a decision support tool that provides a cost-benefit analysis to assist growers evaluate whether applying fungicide to treat PM would be profitable given their weather conditions and the estimated value of the mungbean crop. More robust and reliable estimates of yield responses to different fungicide spray schedules obtained using meta-analytic modelling could be important for validating the assumptions the app makes about the timing of fungicide applications, such as avoiding prophylactic sprays.

Two questions were addressed in our study: i) when in time, relative to PM first signs (prior, during or after), should the first fungicide spray be applied on mungbean to maximize yield protection?; ii) given those timings at which the first spray was made is a second spray worthwhile yield protection? To answer these questions, we systematically reviewed all sources of fungicide trial data for PM control in the eastern Australian mungbean production scenarios that we were able to obtain and conducted a meta-analysis of the effect of different sprays schedules on mungbean yields.

Materials and Methods

Data source and inclusion criteria. As of August 2020, no peer-reviewed study on the efficacy of fungicide on powdery mildew in mungbean was found to be conducted in Australia after searching article databases, Web of Science, Scopus and Google Scholar with the search string: “mungbean AND powdery mildew AND fungicide” and filtering the results by country of publication. On the other hand, we were able to find and gather data from 26 trials reporting the fungicide effect on PM intensity and mungbean yields in databases at the University of Southern Queensland and collaborating institutions, including Northern Growers Alliance and the Queensland Department of Agriculture and Fisheries. Trial locations from these databases represented the main mungbean growing areas in Australia, from Central Queensland to Northern New South Wales. Raw data were available for thirteen trials, the remaining 13 trials reported only the means of each treatment.

Field trials not meeting the following criteria were excluded: i) the field trial was conducted in Australia ii) the date when powdery mildew was first observed; iii) disease severity at the end of the growing season; iv) fungicide application dates; v) the fungicide active ingredient(s); vi) fungicide application dose(s); vii) and crop yield.

Treatments with fungicide active ingredients evaluated in fewer than eight trials were discarded from the analysis. This resulted in the retention of two DMI fungicides (tebuconazole and propiconazole) in the dataset, reducing the initial set of 26 trials to 17 trials. Variance accompanying the treatment means was required for the trials to be included in the meta-analysis. Three trials, 1516/01, 1516/02, 1516/03, were removed for not reporting PM severity variance, resulting in a PM severity meta-analysis on 14 trials (Table 1). Separately, two trials, 1112/01 and 1516/03, lacking grain yield variance were removed from the 17 trials, resulting in a grain yield meta-analysis of 15 trials. All trials included in this analysis were conducted in a randomized complete block design. Further trial details can be found in the supplementary materials and accompanying research compendium.

Treatments of interest. In this study, we were interested in testing whether variations in spray schedules which used triazole fungicide (tebuconazole and/or propiconazole) are more beneficial than the recommended practice. The '*Recommended'* practice refers to a single fungicide spray schedule starting one to three days following the first sign of PM. After inspecting data from the trials which met our inclusion criteria, four other spray schedules were defined based on a combination of spray timing, and if one or more follow-up applications were made after the first spray (coded with the suffix +). A total of five triazole-based spray schedules were then defined: *Recommended* (n_{yield}= 27, $n_{severity}$ = 28); *Recommended+* (n_{yield}= 40, $n_{severity}$ = 41); *Early*, single spray prior to disease detection (n_{yield}= 13, $n_{severity}$ = 13); *Late,* a single spray between seven and 13 days after the first sign of PM (n_{yield}= 17, $n_{severity}$ = 15); and *Late+* (n_{yield}= 19, $n_{severity}$ = 13), a *Late* spray which included one or more follow-up sprays. $n_{severity}$ represents the total number of respective treatments used in the PM severity meta-analysis and $n_{yield}$the total number of respective treatments in the mungbean yield meta-analysis. There were no spray schedule treatments that began between four and six days after the first sign of PM. Given the small number of trials with *Early+* treatments (n_{yield}= 5, $n_{severity}$ = 5) this moderator level was excluded from the meta-analysis.

Response variable and meta-analytic procedures. Following methods in published meta-analyses evaluating the effect of fungicides on crop yield (Paul et al. 2008), we focused this meta-analysis on obtaining estimates of crop yield and proportion disease severity between spray schedules and the nontreated control. Grain yield means of each fungicide treatment, expressed as metric tons per hectare, were either obtained directly from the summaries of trial reports, or summarized from the raw data when available. PM severity was recorded on an ordinal scale from one (no signs of the pathogen) to nine (100 % of plant infested and dropping leaves) (Table 2). The sampling variance was also calculated from the raw data when available or the least squares statistic, using the method described in Ngugi et. al. (2011), when trial data was obtained from summarized trial results.

A preliminary inspection of mean grain yields at the trial level suggested that a normal distribution could be assumed without need for transformation. The distribution of PM severity ratings on the other hand were skewed and needed adjustment. The ordinal one to nine scale was converted to a proportion based on the description of each scale level (Table 2). Converting to a proportion retained the upper (1) and lower (0) scale boundaries and permitted a logit transformation which improved normality of the PM severity response.

The severity scale conversion to a severity proportion was aided by fitting proportion severity to the respective ordinal PM severity scale with a generalized additive model (GAM) using the '*gam*' R package (Hastie 2020). The GAM can be defined by $S_p \sim s(S_o)$ where S_p is a vector of nine severity proportion values equivalent to each level of the ordinal 1 – 9 scale, and S_o the ordinal one to nine scale (S_o). The default 'gam()' '*family*' value, "Gaussian", was used. The smoothing parameter, '*spar*', was set to 0.1 for S_o which allowed a better fit and an R^2 value close to 1. The GAM was used to predict the corresponding percent severity and sampling variance.

Environmental effects between trials would likely lead to spray schedule treatments effects which were correlated within trials. A network meta-analysis, also referred to "two-way unconditional linear mixed model", was chosen because it assumes correlations between treatments within the same trials and makes weighted comparisons between trials even if all treatments are not present within each included trial (Paul 2008; Machado 2017). The model is given by

$$Y_i \sim Norm(\mu + \ \delta, \Sigma + S_i^2),$$

Where Y_i, the response, is either a vector of the grain yield measurements (tonnes per hectare) or a vector of PM severity proportions, for the ith trial over the total number (K) of trials ($i = 1,...K$). Y_i is assumed to be a normal distribution with μ the estimated weighted mean of treatments across all trials; δ is the estimate for each moderator level, in this case '*spray schedule*,' corresponding to each fungicide treatment level; Σ, a 6 x 6 unstructured matrix of treatment variances between trial; and S_i^2 a variance-covariance matrix. Weighted estimates of this random effects model were calculated using the inverse of the model-implied variances (Viechtbauer 2010). The model was fit so 'spray schedule' treatments were added as correlated random effects within each trial and the variance co-variance matrix of the random effects specified as 'unstructured'. This allows the random effects for each spray schedule treatment to have different variances, which are also allowed to be correlated. Each treatment mean/variance entry was given an individual '*id*' variable, which was incorporated as a random effect to the model.

The model was fitted in the R statistical software environment, version 4.0.1, (R Core Team 2020) using the *maximum likelihood* parameter and '*optim'* optimizer with the '*metafor*', version 2-4.0, R package (Viechtbauer 2010). Linear contrasts of the spray schedule moderator estimates and variances for grain yield were used to obtain the mean difference and associated 95% confidence intervals between each spray schedule. These mean differences were used to infer the optimum fungicide spray strategy for maximizing mungbean grain yields. The percentage of variation attributed to within trial variation and between trial variation was approximated for both meta-analyses using the I^2 statistic (Higgins and Thompson 2002).

A stability test was used for the PM severity and yield meta-analyses by excluding one of the trials and running the meta-analysis. This was done 14 or 15 times, for each trial in the respective PM severity or yield meta-analysis. Each of the models with a 'dropped' trial were examined to detect if any of the estimates varied significantly indicating an unstable network meta-analysis.

Results

Trial characteristics and overall summary. Characteristics of the trials which met the study inclusion criteria were summarized in Table 1. Planting dates for the trials ranged from late December to the middle of February. The first signs of PM were observed as early as February 28 and as late as April 12. As expected, PM severity was higher and the mean grain yields were lower in the unsprayed control treatments as compared with those treatments which fungicide was applied (Fig. 1). The median yields at the trial level ranged from 289.4 kg/ha to 2045 kg/ha in the control, while in the spray schedules they ranged from 275.9 kg/ha to 2526.3 kg/ha (Table 1).

In general trials that yielded below 700 kg/ha showed no yield benefit from any fungicide application and two-thirds of the trials produced yields which were on average higher in the fungicide treated plots compared with the no spray control (Table 1).

Meta-analytic estimates. The end of season PM severity was significantly lower in all fungicide spray schedules compared to the no spray controls, with exception to *Early* sprays ($P = 0.313$). The analysis estimated the *Recommended+* spray schedule provided the highest efficacy for controlling PM (Table 3), significantly lowering PM severity compared to all other spray schedules. The other spray treatments, *Recommended* ($P < 0.001$), *Late* ($P = 0.0315$) and *Late+* ($P = 0.0073$), still provided effective control of PM and did not differ significantly from each other with exception to the *Recommended* spray schedule which was significantly higher than a single *Early* application ($P = 0.0116$). Between trial variance accounted for approximately 99.94% of the total PM severity variance as indicated by the I^2 statistic. More than half the PM severity sampling variance which accompanied the means were recorded as zero, which could explain why between trial variance accounted for almost all heterogeneity.

A sensitivity analysis of the PM severity and yield models indicated the consistency for all estimates, with insignificant variation for each moderator when trials were sequentially excluded from the analysis with exception to the exclusion of trial 1617/02 at Missen Flats. Excluding 1617/02 presented the greatest change in estimates with the largest changes occurring in the yield meta-analyses.

The spray schedule effect on mungbean yields were somewhat similar to the PM severity meta-analysis. All spray schedules, except for *Early* ($P = 0.946$), resulted in a significant yield increase relative to the unsprayed controls (Table 4). For those spray schedules, the difference in yield relative to the control ranged from 130.1 to 189.1 kg/ha, with the highest estimated yield increase produced by *Recommended+* followed by *Recommended*, *Late* and *Late+* (Table 4). Between trial heterogeneity was also high in the yield meta-analysis, consisting of 99.66% of the model variance according to the I^2

statistic test. A Wald-test of moderators indicated a disease pressure in the no spray control was significant (P = 0.047) when improving yield protection estimates for each spray schedule. However, due to low replication between some disease pressure categories and no *Late+* spray schedules observed in low disease pressure trials, further analysis was not pursued.

An inspection of log-likelihood profile plots showed the models for each random interactive term provided a reasonable estimate of τ^2, with no indication the variables were over-fit.

Discussion

The current advice provided to eastern Australian mungbean growers for when to commence fungicide applications for controlling powdery mildew is to spray at the first appearance of the disease (Thompson 2016; Sparks and Kelly 2017). Our meta-analysis corroborates the current advice but also suggests that if the first spray is delayed by up to one to two weeks mungbean yields may still be protected given the statistically similar results of the *Late* categorized spray schedules to the *Recommended* practice. Reducing PM severity however was most effective in the *Recommended+* spray schedule despite the results of the yield analysis. Regardless, if the goal is to save yield and maximize return these results are reassuring for mungbean growers who lack time and resources to scout crops regularly for disease or for situations when logistic issues prevent growers from getting machinery in the paddock immediately after PM is spotted. A flexible window for commencing a spray program permits growers to consider better planning for their integrated pest management by timing sprays in combination with other chemicals and thus reduce costs with spray application. However, if the grower decides to apply a second spray, consideration should be given to the fungicide withholding periods, which in Australia require the second application to be applied at no earlier than 10 to 14 days after the first application, and not within 21 days of harvest (Australian Pesticides and Veterinary Medicines Authority 2014). Time permitting, a second spray after a "*Late*" application may not be necessary, as suggested by our results (Table 4). More research is needed to evaluate whether crop age at the first sign of PM may influence potential crop yield reductions given the timing of spray schedule interventions.

Results from a stability analysis on the yield meta-analysis shows the removal of trial 1617/02 at Missen Flats caused the greatest change in yield estimates and lowered confidence in the differences between treatments. This shows that results from this trial had greater weight in the meta-analysis due to lower sample variances. In addition, the Missen Flats trial produced higher yields (Table 1) and was subject to high disease pressure resulting in greater losses due to the disease, which may also have contributed to this trial having the most influence on the meta-analysis estimates. The number of trials collated in this meta-analysis could be considered small, however results from future trials could easily be added to the results published here to improve confidence for the best fungicide spray schedule timing.

In this study, between trial variance accounted for almost all variance for both yield and disease severity meta-analyses. Climatic variation and management differences between the trials, such as planting date and supplemented irrigation, are likely to be major contributing factors to the between trial variance.

According to the Australian Mungbean Association sowing guide (Australian Mungbean Association n.d.), mungbeans should not be sown later than January in the Darling Downs region of southern Queensland, the region where most of the trials were undertaken. If the planting guide is adhered to, powdery mildew may present later in the crop cycle and yields may be at a lower risk from powdery mildew, reducing the requirement for fungicide applications. An example of this is the 2013 trials, Premer (AM1303), Goolhi (AM1305) Marys Mount (AM1304) and Millmerran (BB1305) where PM manifested 60 days after sowing or later (Table 1), approximately when the plant would be filling pods. The trial reports indicated significant differences in powdery mildew severity between the fungicide treatments, however none of the trials showed a significant difference in grain yield between the same treatments (Northern Growers Alliance 2013a, 2013b, 2013c, 2013d). Crop age at first infection may also explain the large amount of between-trial heterogeneity. Therefore, in lieu of further research, discretion is still required to determine if fungicide applications are necessary, and consideration given to the crop growth stage and forecast weather conditions at the first sign of PM.

Early detection of PM remains vital for an effective fungicidal control response. Data from the trials included in this experiment show regardless of crop sowing date, PM establishes on average in the month of March, which marks the beginning of autumn in Australia. Such information, together with additional observations, may permit models to predict the likely onset of the disease given weather parameters, providing an early warning system for growers to scout their crop for signs of powdery mildew. The results herein suggest, ideally, that inspections for the first signs of PM occur weekly in March to ensure timely fungicide applications. Scouting at intervals greater than 12 to 13 days might risk crop losses if a spray schedule does not commence within the aforementioned spray window. More work is needed to understand when "*Late*" fungicide applications are too late. However regardless of the number of sprays, fungicide applications commencing at the *Recommended* time on average were more effective at limiting PM severity and protecting mungbean yields.

The approximate costs of applying tebuconazole fungicide at $ 4.18 AUD/ha, if fungicide is purchased at $ 15 AUD/L (Simpfendorfer and Taylor 2011) and application cost are $ 2 AUD/ha (Queensland Government 2019). This meta-analysis estimates average yield savings of between 137.8 kg/ha (SE = 33.9) (*Recommended*) and 189.1 kg/ha (SE = 53.0) (*Recommended+*). Assuming mungbean is sold at $ 1200 AUD/t, these yield savings would save between $ 71 to 234 AUD/ha for a single application at first sign and $ 83 to 337 AUD/ha if a follow-up application is made. Such profit levels and efficacy for controlling visual signs of disease may tempt growers into applying fungicide to control diseases such as powdery mildew when they are unnecessary or unlikely to result in a financially beneficial yield saving. Excessive use of fungicides is likely to lead to ongoing problems such as fungicide resistance. The evolution of fungicide resistance can occur quickly, especially when spray schedules are not designed with potential fungicide resistance in mind. Powdery mildew is one such group of fungal pathogens with an extensive track record of rapidly developing fungicide resistance. *P. xanthii* is categorized by the Australian Fungicide Resistance Action Committee (FRAC) as a “High Risk” candidate to evolve fungicide resistance (Fungicide resistance action committee 2019; Peterson 1973; McGrath 2001; Chin et al. 2001).

To extend the time that a fungicide remains effective against the target pathogen, the strategic use of the fungicide must be considered. To aid in making these decisions and devising a good strategy, DSS tools such as the *PowderyMildewMBM* app consider crop growth stage and weather, informing users when deciding whether to spray or not to spray (Department of Primary Industries and Regional Development 2019). Using these such tools can reduce unnecessary and unprofitable fungicide applications, which may help lead to the development of fungicide resistance. To offer more benefit for future research, experiments should record physiological maturity of the crop throughout the season so "crop age" might be considered as a covariate in future analyses.

Currently, the recommendations that are advised to mungbean growers appear to be the best practices for reducing losses due to powdery mildew. Care needs to be taken to adhere to them, especially avoiding prophylactic sprays, to limit the development of fungicide resistance in the powdery mildew pathogen populations. While the number of included trials in these meta-analyses is low, this study provides direction for future powdery mildew control research in Australian mungbean. Future trials might build on this work to provide greater certainty as to when *Late* fungicide applications would be too late to protect yield losses due to the disease. Given the high value of mungbean at the farm-gate, further work could be done in this area that would benefit the Australian mungbean industry.

Supplemental Material

Supplementary material can be found in the following research compendium. https://openplantpathology.github.io/Mungbean_PM/

Data Availability

All data and code used in the preparation of this manuscript can be found in the associated research compendium.

Conflict of Interest Statement

The authors of this paper have no conflicting interest in the research presented in this manuscript.

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Tables and Figures

Table 1. Trial summaries which met the inclusion criteria for yield and powdery mildew (PM) severity meta-analyses.

Trial code	Location	Year	Sowing date	PM onset[a]	n[b]	Control median PM severity[c]	PM severity range	Control median yield	Yield range (t / ha)
1011/01	Hermitage	2011	2011-01-24	2011-03-28	4	4.83 (2)	2 - 2.33	1.525	1.544 - 1.769
1011/02	Kingaroy	2011	2011-02-02	2011-03-22	6	7.83 (2)	3.33 - 5.33	0.798	0.73 - 1.059
1112/01	Gatton	2012	2012-02-20	2012-04-02	7	7.5 (1)	2 - 6.3	0.738	0.81 - 0.948
1112/02[d]	Kingaroy	2012	2012-02-03	2012-03-12	7	8 (1)	1.7 - 8	0.751	1.036 - 1.323
AM1303	Premer	2013	2012-12-28	2013-02-28	4	8 (1)	2 - 7.83	1.422	1.334 - 1.45
AM1304	Marys Mount	2013	2012-12-24	2013-03-16	2	3 (1)	3.17 - 3.17	1.094	1.265 - 1.265
AM1305	Goolhi	2013	2013-01-23	2013-03-25	4	9 (1)	1 - 3.75	0.694	0.604 - 0.722
BB1305	Millmerran	2013	2013-01-12	2013-03-13	4	8 (1)	1.62 - 8	0.802	0.744 - 0.803
1415/01	Hermitage	2015	2015-01-19	2015-03-16	5	7.8 (1)	5.4 - 6.6	2.045	2.018 - 2.176
1516/01	Hermitage	2016	2016-02-03	2016-03-08	7	8 (1)	3 - 7.5	1.803	2.141 - 2.37
1516/02[e]	Kingaroy	2016	2016-02-11	2016-03-09	7	8.25 (1)	2.25 - 7.75	0.811	0.873 - 1.034
1617/01[e]	Hermitage	2017	2017-02-13	2017-03-24	39	8 (9)	5.33 - 8	0.474	0.327 - 0.683
1617/02	Missen Flats	2017	2017-01-27	2017-03-07	39	9 (9)	7.67 - 9	1.505	1.13 - 2.526
1718/01	Wellcamp	2018	2018-02-13	2018-03-21	18	8.17 (6)	5.67 - 7.67	1.091	1.084 - 1.69
1819/01	Hermitage	2019	2018-02-04	2018-04-12	4	7.5 (1)	5 - 7.17	0.587	0.543 - 0.571
1819/02	Hermitage	2019	2018-02-18	2018-04-12	4	7.83 (1)	4.6 - 7.33	0.289	0.276 - 0.312

[a] Date of first powdery mildew (PM) observation.

[b] number of spray treatments per trial (n).

[c] Bracketed numbers following nontreated control PM severity refers to the number of pooled control treatments summarized.

[d] Trials which reported PM severity variance and not yield variance and therefore excluded in the yield protection meta-analysis.

[e] Trials which did not report powdery mildew (PM) severity variance and therefore excluded in the PM severity meta-analysis.

Table 2. Powdery mildew severity rating scale and calculated percent severity for each ordinal rating

Severity rating	Description	Equivalent percent severity
1	No sign of powdery mildew	0.00
2	Small colonies in the lower 1/3 of canopy with up to 75% of plants infested	16.50
3	Colonies in lower half of canopy with more than 75% of plants infested	43.50
4	Colonies in lower 2/3 of canopy with up to 75% of plants infested	49.50
5	Colonies in lower 2/3 of canopy with more than 75% of plants infested	57.42
6	Colonies in lower 2/3 of canopy with 100% of plants infested	66.00
7	Colonies in lower 2/3 of canopy with 100% of plants infested, some plants with colonies in the top 1/3 of the canopy	75.00
8	Colonies all the way to the top of the plant with more than 75% of plants affected	87.00
9	Colonies to the top of the plant with severe leaf drop	100.00

Table 3. Estimated powdery mildew severity mean difference for each spray schedule treatment to the unsprayed control treatments. Meta-analysis estimates were back transformed using an inverse logit. Data were obtained from the gray literature reports of (k) field trials undertaken in Eastern Australia.

Moderator	***N*[a]**	***k*[b]**	***mu*[c]**	***se***	***P*[d]**	***CI_L*[e]**	***CI_U*[f]**
Early	13	3	-0.0433	0.0287	0.313	-1.1047	-0.1841
Recommended	28	12	-0.2725	0.0261	< 0.0001	-1.3974	-0.4768
Recommended+	41	11	-0.4408	0.0257	< 0.0001	-1.5522	-0.6317
Late	15	5	-0.1458	0.0327	0.0315	-1.3091	-0.3885
Late+	13	2	-0.2101	0.0333	0.0073	-1.4000	-0.4795

[a] Number of treatment means categorized to each spray schedule.

[b] Number of trials with the respective spray schedule.

[c] Estimated mean disease severity.

[d] Indicates the significance between each respective spray schedule and the no spray control (intercept).

[e] Lower range of the 95% confidence interval.

[f] Upper range of the 95% confidence interval.

Table 4. Estimated mungbean yield mean difference to the no spray control (intercept) for each spray schedule treatment. Yield estimates (μ) were calculated from a network meta-analysis of data obtained from gray literature reports of 'k' field trials undertaken in Eastern Australia.

Moderator	*N*[a]	*k*[b]	*μ*[c]	*se*	*CI_{L}*[d]	*CI_{U}*[e]	*P*[f]
Early	13	3	0.0029	0.0439	-0.0830	0.0889	0.9464
Recommended	27	13	0.1378	0.0339	0.0713	0.2043	< 0.0001
Recommended+	40	12	0.1891	0.0530	0.0853	0.2930	0.0004
Late	17	7	0.1374	0.0440	0.0512	0.2237	0.0018
Late+	19	4	0.1301	0.0578	0.0168	0.2433	0.0244

[a] Number of treatment means categorized to each spray schedule.

[b] Number of trials with the respective spray schedule.

[c] Estimated mean yield determined by the meta-analysis.

[d] Lower range of the 95% confidence interval.

[e] Upper range of the 95% confidence interval.

[f] Indicates the significance between each respective spray schedule and the no spray control (intercept)

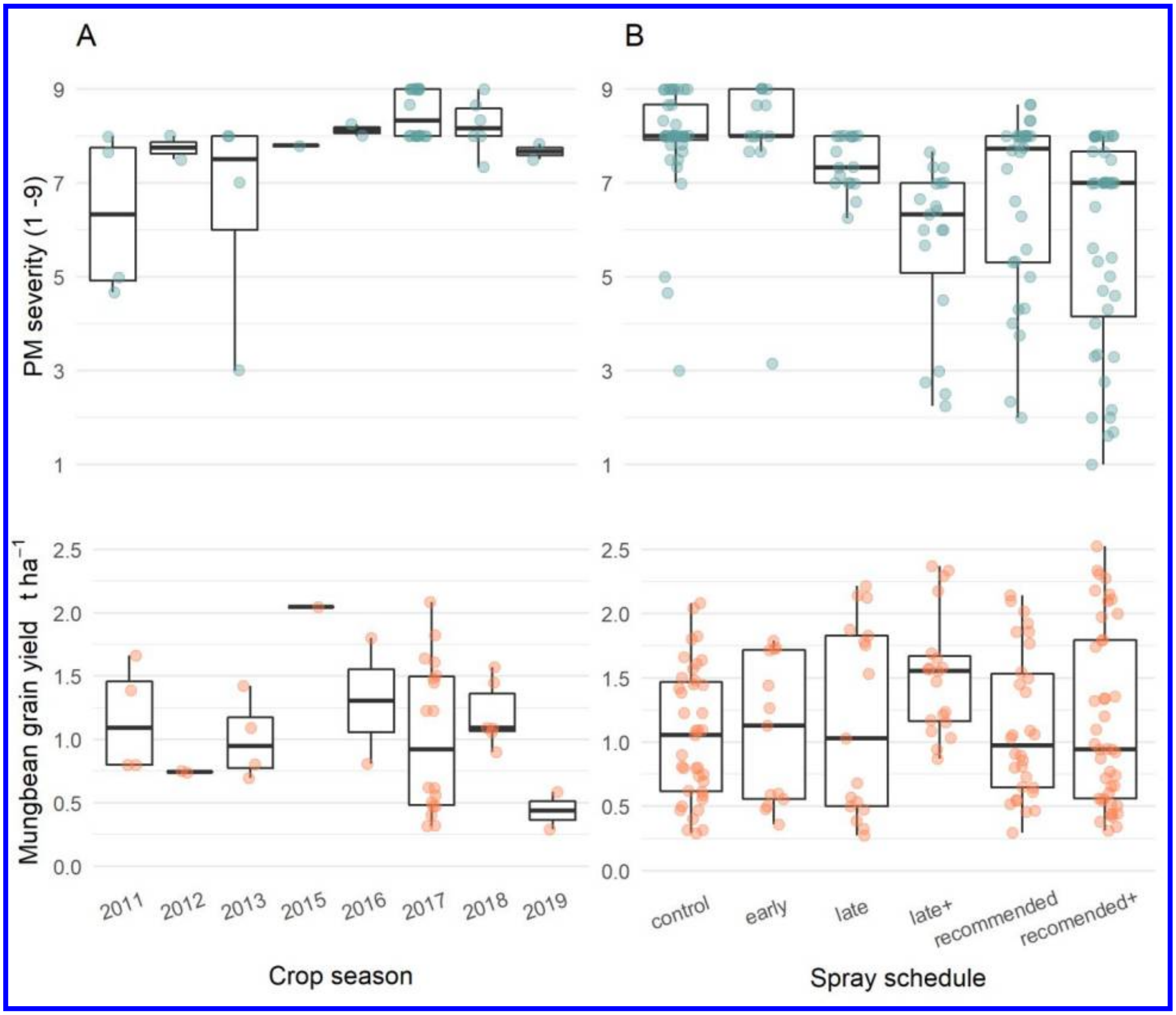
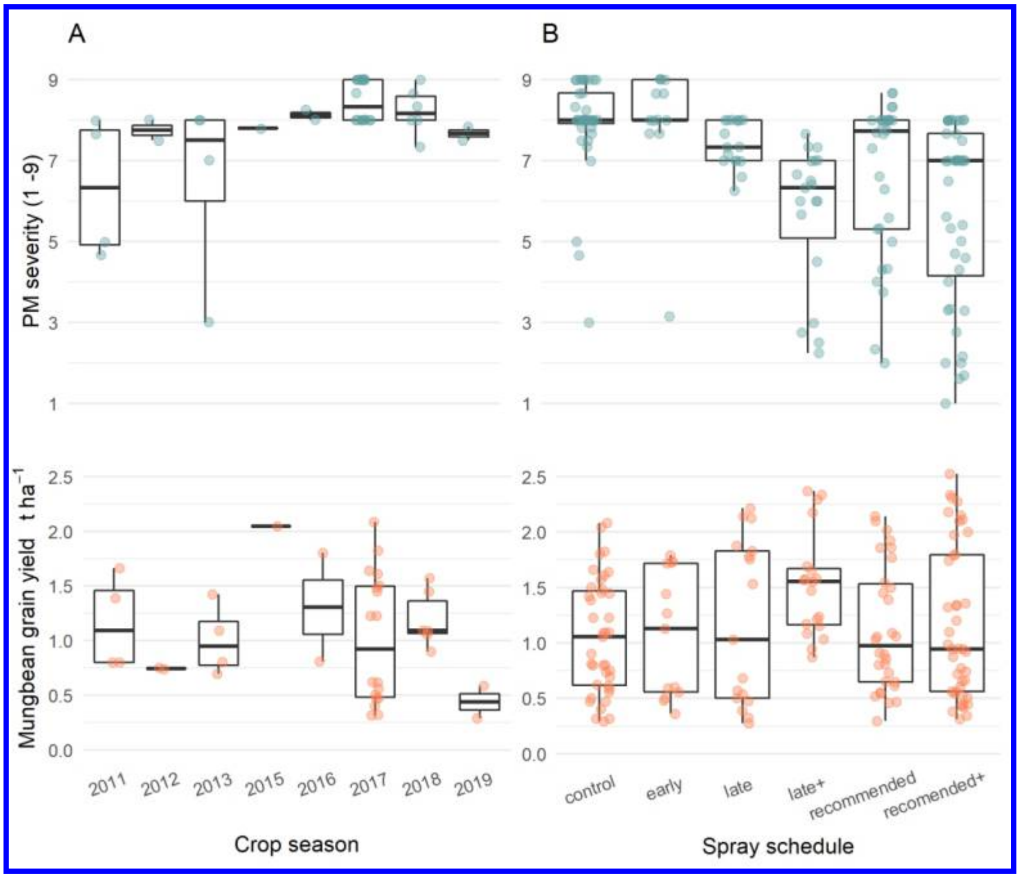


Figure 1: Box plots of the unsprayed control treatment means for both PM severity (top) and crop yield (bottom), indicating within-season variation **A,** and trial treatment means for each spray schedule **B**. The middle box plot line indicates the median, box boundaries indicate the lower and upper quartiles; circles indicate trial treatment means for each respective crop season and spray schedule.

Data and code for reproducibility

https://github.com/openplantpathology/Mungbean_PM



Box plots of the unsprayed control treatment means for both PM severity (top) and crop yield (bottom), indicating within-season variation (**A,**), and trial treatment means for each spray schedule **B.** The middle box plot line indicates the median, box boundaries indicate the lower and upper quartiles; circles indicate trial treatment means for each respective crop season and spray schedule.

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