RESEARCH ARTICLE

Profitability of fungicide applications for managing soybean rust in scenarios of variable efficacy and costs: a stochastic simulation

Kaique S. Alves¹ • Jhonatan P. Barro¹ • Mariana Guimarães¹ • Emerson M. Del Ponte^{1,*}

Affiliations:

¹ Departamento de Fitopatologia,
Universidade Federal de Viçosa,
36570-900, Viçosa, MG, Brazil

***Corresponding author:**

Emerson M. Del Ponte, delponte@ufv.br

Data Availability Statement: The data that support the findings of this study are openly available in the Open Science Framework project at doi.org/10.17605/OSF.IO/CE8H5.

Funding: This study was financed in part by the 'Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil' (CAPES) - Finance Code 001. The second author is thankful to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for providing scholarships. The fourth author received a research fellowship from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)/Brazil.

Keywords: *Phakopsora pachyrhizi*, *Glycine max*, chemical control, economic analysis, risk analysis, Monte Carlo simulations

Abstract

Soybean rust (SBR) in Brazil is controlled with fungicides, which have shown variable, eventually declining, efficacy. A Monte Carlo simulation framework was proposed to approximate profitability depending on the fungicide program's efficacy and total cost. Probability distributions were fitted to slopes and intercepts of the disease-yield relationship and severity in the untreated plots reported in the literature, as well as historical records of soybean price. Simulations of disease reduction conditioned to predefined control efficacy and total application costs were split into scenarios that combined two categories of severity (high and low) and two attainable yield classes (high and low). These categories were defined based on the median of severity (57.8%) and median of the intercept (yield when severity is zero, 2995.1 kg/ha). Probability matrices were constructed relating fungicide efficacy and costs. A higher frequency of break-even events occurred in scenarios of high disease pressure and higher yield. Yearly simulations, starting with 79.4% efficacy, assuming two rates of decline determined for tebuconazole (high decline), showed that the program may remain profitable during the first 5 to 7 years of use. Contrasting to cyproconazole, a fungicide that would be profitable during the entire decade. These simulations can be useful to aid in decision-making when planning fungicide programs. This approach can be adapted to other diseases of soybean and other crops as long as damage functions are available. An interactive web app was developed to perform the simulations accessible at alvesks.shinyapps.io/rusty-profits/.

Introduction

Soybean rust (SBR, *Phakopsora pachyrhizi* Syd. & P. Syd.) is the most economically significant disease for soybean worldwide. In Brazil, this disease can be more severe where the off-season (winter) climate does not restrict the survival of the fungal pathogen and the within-season (summer) climate is generally favourable for epidemics (Del Ponte *et al.*, 2006; Del Ponte & Esker, 2008; Godoy *et al.*, 2016). The disease was introduced to Brazil in 2001, and the impact on yield in commercial crops was devastating, but subsequently minimised with the use of improved control methods. Severe yield losses, as high as 78%, have been reported in unmanaged field experiment plots conducted over a decade (Dalla Lana *et al.*, 2015). Today, the combination of chemical, cultural, and legislative methods is the most effective management strategy to protect soybean against significant yield losses (Godoy *et al.*, 2016). Delayed onsets of soybean rust, on a regional basis, has been observed after the enforcement of a soybean-free period across several Brazilian states, as a result of shifts in sowing date (earlier) and cultivars (early-maturing and disease-resistant) as disease avoidance principles (Godoy *et al.*, 2016).

Although much has been learned to manage soybean rust effectively, annual economic losses due to soybean rust are no less than US\$ 2 billion (mainly fungicide costs), positioning Brazil as a major market for chemical fungicides (Godoy *et al.*, 2016). During the soybean growing season, a well-planned fungicide spray program is indispensable and both fungicide composition and the frequency of applications varies across regions and over the years. Extensive field research focused on monitoring and comparing individual fungicide performance has been essential for adjustments in fungicide programs (Dalla Lana *et al.*, 2018; Godoy *et al.*, 2016; Godoy, Bueno & Gazziero, 2015; Scherm *et al.*, 2009).

The effectiveness of a fungicide spray program depends on the expected control efficacy, determined experimentally, which varies according to the program itself (active ingredients alone or in premix, dose, timing, and the frequency of applications) as well as the application technology and seasonal weather, which affects disease risk (Roehrig *et al.*, 2018; Del Ponte *et al.*, 2006, 2011). Adjustments in spray programs are necessary to maximise effectiveness and profits; the latter depends on fungicide cost and soybean selling price which varies among regions and the year within regions.

The most common adjustment in fungicide programs targets the selection of active ingredients, while the number of sprays is relatively less variable among the regions due to the widespread use of calendarized applications (Beruski *et al.*, 2020). While some fungicides have declined in use

or abandoned due to technical reasons, such as failure of control in the field, others have been introduced to the market (Godoy *et al.*, 2016). An example of serious control failure is tebuconazole (DMI), one of the first cost-effective options that began losing efficacy more than ten years ago (Dalla Lana *et al.*, 2018). More recently, a trend towards declining efficacy has been noticed for premixes of DMIs and quinone outside inhibitor (QoI) fungicides (Godoy *et al.*, 2016; Dalla Lana *et al.*, 2018). Earlier observations of reduced efficacy paralleled reports of the presence of less sensitive *P. pachyrhizi* strains to tebuconazole in Brazil (Brent, K. J. & Hollomon, D. W., 1995; Schmitz *et al.*, 2013). Similarly, mutations associated with QoIs and succinate dehydrogenase inhibitor (SDHI) fungicides, the most recent group introduced to compose dual or triple mixtures, have recently been found (Klosowski *et al.*, 2018, 2016; Simões *et al.*, 2018).

When the options of highly effective fungicides are reduced and a reduction in the number of sprays is required to mitigate the risk of fungicide resistance, control efficacy will invariably reduce, thus reducing yield savings, given the strong association between severity and yield (Dalla Lana *et al.*, 2015). Although maximising yield is a goal, the most important outcome is the odds of a fungicide program being profitable. A recent study compared calendar-based applications and warning systems to time fungicide spray for soybean rust control and showed that the breakeven probability did not vary among them; the increased costs associated with extra sprays did not translate into higher margins of profit than fewer sprays (Beruski *et al.*, 2020). Informed decisions that take risk information into account is a valuable tool to minimise the risk of fungicide resistance and prolong fungicide efficacy and usage.

Previous studies have addressed similar questions regarding the profitability of fungicides. In most cases, the analyses are based on meta-analytic estimates of the mean and variance of the yield response, using large size empirical datasets, for a range of combinations of fixed fungicide costs and crop prices (Barro *et al.*, 2019; Willbur *et al.*, 2019; Molina *et al.*, 2019; Machado *et al.*, 2017; Paul *et al.*, 2011; Shah & Dillard, 2006; Wise *et al.*, 2019; Duffeck *et al.*, 2020).

In previous studies, mean yield gain (assuming normality) was used to calculate the break-even probability, subsequently, we propose implementing a stochastic simulation approach, as used elsewhere (Shah & Dillard, 2006; Willbur *et al.*, 2019), to fit theoretical distribution models to existing datasets describing the soybean rust severity-yield relationships (Dalla Lana *et al.*, 2015). The (practical) questions addressed in this study are: 1) what is the maximum cost allowed for a fungicide program, knowing its efficacy, to be

profitable (income > cost) in scenarios of low/high yield and low/high disease pressure?; and 2) How long will a fungicide program remain profitable under declining efficacy of the fungicides? To achieve our aims, Monte Carlo simulations were performed to construct breakeven probability matrices for a range of scenarios to aid in decision-making during planning a fungicide program. An interactive web application was developed to perform the simulations using values and ranges of the variables defined by the user.

Material and methods

General simulation framework

Our framework is based on stochastic simulations of break-even events (income $\geq$ cost) from using a fungicide program for a range of efficacies and total cost (fungicide + operational cost). The income is determined by the product of (saved or gained) yield, due to the reduction in disease severity promoted by fungicides, and the soybean selling price. Probability distributions were fitted to a 1) historical series of soybean prices and 2) the empirically determined regression coefficients for the relationship between SBR severity and soybean yield (Dalla Lana *et al.*, 2015). We simulated reductions of severity (also simulated by a probability distribution fitted to the severity on untreated plots) according to a predefined efficacy to simulate yield gain. We subsequently defined a range of cost and efficacy values to derive a decision matrix for two scenarios of attainable yield and disease pressure (conditioned to the simulated SBR severity in unmanaged crop). Finally, we simulated annual curves for the probability of breakeven events assuming two rates of decline in fungicide efficacy, determined in previous studies (Dalla Lana *et al.*, 2018), and three values of soybean selling prices.

Equations

For a fungicide spray program to break-even, the total cost (C , US\$/ha) should be lower than or equal to the income (I , US\$/ha), thus $I \geq C$, where C is given by

$$C = n (C_f + C_{op}), \quad (1)$$

with n being the number of sprays performed, C_f is the cost of one fungicide spray, and C_{op} the operational cost of one spray per hectare (US\$/ha). The income (I) is given by

$$I = P \Delta_Y, \quad (2)$$

where P is the soybean price (US\$/kg) and Δ_Y the increase in yield per hectare (kg/ha) due to the fungicide application given by

$$\Delta_Y = Y_f - Y_n, \quad (4)$$

where Y_f and Y_n represents the yield obtained with and without fungicide application, respectively. Therefore, from $I \geq C$, we obtain

$$Y_f - Y_n \geq \frac{C}{P}. \quad (5)$$

The relationship between yield and soybean rust severity index accounting for defoliation (thereafter SBR severity) (Dalla Lana et al. 2015) can be given by

$$Y = Y_{max} - (-\alpha S Y_{max}), \quad (6)$$

where Y_{max} represents the attainable yield (no SBR), S represents SBR severity (proportion) and α represents the yield damage coefficient (%/percentage point) (Dalla Lana et al., 2015). Therefore Y_f and Y_n can be written as

$$Y_f = Y_{max} - (-\alpha S_f Y_{max}) \text{ and} \quad (7)$$

$$Y_n = Y_{max} - (-\alpha S_n Y_{max}), \quad (8)$$

respectively, where S_f and S_n are the SBR severities (proportion) for fungicide-treated and non-treated scenarios. The severity in the fungicide-treated scenarios (S_f) can be calculated from the severity in the non-treated scenarios (S_n) and the fungicide efficacy (λ ; $0 \leq \lambda \leq 1$) given by

$$S_f = S_n (1 - \lambda). \quad (9)$$

Probability distributions

SBR severity in the non-treated plots ($n = 250$) was assumed to follow a Beta probability distribution $S_n \sim \text{Beta}(\alpha_b, \beta_b)$. The parameters were obtained via fitting of the Beta cumulative density function (CDF) to the empirical CDF of severity (Dalla Lana et al., 2018).

Values on the intercepts (β_0) and slopes (β_1) parameters from the fit of the linear regression model to the data on the relationship between SBR severity and soybean yield (kg/ha) were obtained from publicly available raw data (Dalla Lana et al., 2015). The empirical CDFs of both coefficients were constructed. A Normal distribution function fitted β_0 and a Gamma distribution function fitted β_1 denoted by $\beta_0 \sim N(\mu, \sigma^2)$ and $\beta_1 \sim \text{Gamma}(\alpha_g, \beta_g)$,

respectively. The β_1 values were all negative and the Gamma distribution assumes only positive values, thus simulated values were multiplied by -1 during simulations as well as in the fitting procedure.

Because β_0 and β_1 were significantly correlated ($r = -0.21$, $P = 0.001$), a Gaussian copula procedure was used to simulate the bivariate distribution (Ross, 2013). We simulated a bivariate normal distribution X where $X_1 \sim N(0, 1)$ and $X_2 \sim N(\rho X_1, 1 - \rho^2)$, where ρ is the correlation coefficient between the random β_0 and β_1 . Then the Normal distribution function of the simulated value is obtained and used to obtain the corresponding quantiles in the original distribution of β_0 (Normal) and β_1 (Gamma), respectively. Being β_0 and β_1 available, the relative yield loss (α) can be obtained by (Madden, Hughes & van den Bosch, 2007)

$$\alpha = \frac{\beta_1}{\beta_0} 100. \quad (10)$$

The attainable yield (Y_{max}) was obtained from β_0 , representing yield when SBR is absent ($S = 0$). The soybean price (US\$/kg) was assumed to be Normally distributed $P \sim N(\mu, \sigma^2)$. The mean and variance of soybean price (see P in Table 1) were calculated from data available online (agrolink.com.br/cotacoes) from January 2018 to October 2019 for five production states in Brazil: Rio Grande do Sul, Paraná, Goiás, Mato Grosso, and Tocantins. The two-sample Kolmogorov-Smirnov test (KS-test) was used to test the null hypothesis ($P \leq 0.05$) that simulated and observed data came from the same distribution.

Stochastic simulations

Probability matrices

A total of 40,000 Monte Carlo simulations for scenarios that combined a range of fungicide efficacies ($\lambda = 0$ to 100%, by 5%) and application costs ($C =$ US\$0.00 to US\$270.00 by US\$15.00) totalling 399 scenarios were run. The number of applications (n) is implicit in the total cost. The probability of breakeven, denoted as $Pr(I \geq C)$ was calculated based on the relative frequency of favourable events, that is $I \geq C$ in all simulation runs.

The simulated severity data (S_n) and attainable yield (Y_{max}) were split into two categories each representing "seasonal disease pressure" and "attainable yield level", based on the median: low severity ($S_n \leq 57.8\%$) and high severity ($S_n > 57.8\%$); and low yield ($Y_{max} \leq 2995.1$ kg/ha) and high yield ($Y_{max} > 2995.1$ kg/ha).

Annual curves of profitability under declining efficacy

In our previous study, a meta-regression analysis showed significant annual declines in the efficacy, at various rates depending on the fungicide, obtained from cooperative trials conducted across several locations and years in Brazil (Dalla Lana et al., 2018). We selected the regression parameters [intercept (β_0) and slope (β_1)] estimated for Cyproconazole (CYPR) and Tebuconazole (TEB) fungicides, considered to represent a low and high annual rate of decline, respectively.

In the above-mentioned study, the regression parameters were obtained from the fit of a meta-regression model including year (year) as a covariate to the log-response ratio (severity in the treatment/severity in the untreated check), given by

$$\ln \left(\frac{\bar{S}_f}{\bar{S}_n} \right) = \beta_0 + \beta_1 \text{ year} \quad (11)$$

Since the β_0 is used to calculate the initial control efficacy, thus to facilitate comparisons, we used the β_0 value from TEB estimate: -1.581 (SE = 0.065), which gives ~ 79.4% of control efficacy. The β_1 values were 0.147 (SE = 0.012) and 0.061 (SE = 0.015) for TEB and CYPR, respectively (Dalla Lana et al. 2018). The parameters were assumed to be normally distributed with a mean equal to its estimate and standard deviation equal to the standard error (SE). Since the control efficacy (λ) can be calculated as

$$\lambda = 1 - \frac{\bar{S}_f}{\bar{S}_n}, \quad (12)$$

the yearly control efficacy can be calculated from equation 11 as

$$\lambda = 1 - \exp(\beta_0 + \beta_1 x). \quad (13)$$

Ten consecutive years of fungicide use and three fixed values of application costs (C) (US\$75.00, US\$100.00, and US\$125.00) were used. The probability distributions of all variables needed for the simulation were the same described in the previous sections. A total of 30,000 Monte Carlo simulations were performed for each year, from which probabilities of breakeven were calculated.

Tools, reproducibility, and software application

Probability distributions were fitted to the data using `nlsLM()` function of the *minpack.lm* (Elzhov et al., 2016) R package, which performs nonlinear least-squares estimates of parameters using the Levenberg-Marquardt algorithm. The `ks.test()` function of R (R Core Team, 2020) was used to perform the two-sample Kolmogorov-Smirnov test. The

`lm()` function of R was used to perform linear regression between yield gain and efficacy. Pearson's correlations were calculated using the `correlation()` function of the *agricolae* package (Mendiburu, 2020). Graphical work was done using the *ggplot2* (Wickham, 2016) and *patchwork* (Pedersen, 2020). All RMarkdown scripts, observed and simulated data were developed in R version 4.0.3 and are available at <https://git.io/Jk7x2>.

The scripts used in the study were included in an interactive shiny web application (Chang *et al.*, 2020). We introduced a few modifications in the framework to allow more flexibility to the user. Minimum and maximum values can be defined for soybean price and cost. In such cases, Uniform, rather than a Normal distribution function, was assumed and the values randomly drawn from the selected interval at each simulation run. Finally, the number of runs, program efficacy, disease pressure (overall, low or high), and yield level (overall, low, high) can be defined by the user.

Results

Parameters of the probability distributions

The parameters and shapes of the empirical and simulated probability distributions functions (PDFs) fitted to observed data of disease severity (S_n), soybean prices (P), and two damage coefficients (β_0 and β_1) are shown in Table 1 and Fig. 1, respectively. The P -value of the KS-test suggested that the simulated and the observed values were drawn from the same distribution for all four variables (P -value > 0.95; Table 1).

Table 1: Parameters of the theoretical distributions fitted to empirical distributions of severity on the untreated check (S_n) of soybean rust, soybean price (P) for the period from January 2018 to October 2019, intercepts (β_0) and slope (β_1) obtained for the relationship between severity and soybean yield at the trial level.

Variable	Theoretical probability distribution	Parameter values	Constraint	P -value ^a
S_n	$S_n \sim \text{Beta}(\alpha_b, \beta_b)$	$\alpha_b = 1.707$, $\beta_b = 1.266$	-	0.953
P	$P = N(\mu, \sigma^2)$	$\mu = 0.293$, $\sigma = 0.021$	-	0.996
β_0	$\beta_0 \sim N(\mu, \sigma^2)$	$\mu = 2977$, $\sigma = 853.5421$	$\beta_0 \geq 0$	0 .999
β_1	$\beta_1 \sim \text{Gamma}(\alpha_g, \beta_g) - 1$	$\alpha_g = 3.0443$, $\beta_g = 0.1683$	-	0 .999

^a P -value for the Two-sample Kolmogorov-Smirnov test under the null hypothesis that simulated and observed data come from the same distribution

Figure 1: Empirical histograms and probability density function (solid lines) fitted to (A) severity in non-treated plots, (B) soybean price, and the (C) intercept and (D) slope for the relationship between soybean rust severity and crop yield (Dalla Lana et al. 2015) obtained from 250 trials.

The Pearson's correlation coefficient between simulated damage coefficients (20,000 simulations) was -0.20 ($P\text{-value} < 0.001$), very similar to the value obtained with the empirical dataset (-0.21 , $P\text{-value} < 0.001$) (Fig. 2A and Fig. 2B). The central tendency and variability statistics, as well as the shape of density (Fig. 2C and Fig. 2D) and cumulative (Fig. E) distributions of the simulated and observed percent relative yield loss (α), were very similar among them (Fig. 2C and Fig. 2D). The means/medians were $-0.63/-0.54$ and $-0.63/-0.53$ and the variances were 0.13 and 0.14 , for the observed and simulated distributions, respectively. The KS-test suggested that their empirical and simulated distributions were drawn from the same distribution ($P\text{-value} = 0.604$) (Fig. 2C). In a few cases, simulations of β_0 and β_1 tended to infinity; hence unrealistic outcomes of α were generated. To overcome this issue, we truncated the distribution of α into the -3 to 0 interval, based on the shape of its empirical histogram (Fig. 2).

Figure 2: Correlation between (A) empirical and (B) simulated intercepts and slopes estimated for the linear relationship between soybean rust severity and crop yield determined in a previous study for 250 trials (Dall Lana et al. 2015). Histograms and respective means and medians of the relative percent yield loss [percentage per percent point (p.p.) increase in severity] calculated using equation 10, for (C) empirical and (D) simulated intercepts and slopes. (E) Comparison between the empirical and simulated cumulative probability distribution of relative percent yield loss.

Yield gain and fungicide efficacy

Overall, both in absolute and relative terms, soybean yield gains from using a fungicide program increased linearly with the increase of its efficacy (Fig. 3). According to the first-order linear model fitted to their relationship, a 9.61 kg/ha (or 1.90 p.p.) increase in yield was predicted, overall, for each unitary percent increment in fungicide efficacy. When the data were split into two scenarios of "disease pressure", yield gain was generally lower in trials where environmental conditions were less favourable for the disease compared with those of more favourable conditions (Fig. 3). Yield gains varied between the attainable yield levels, in which higher returns in yield are expected for high-yield situations compared to the low-yield scenarios (Fig. 3).

Figure 3: Soybean yield gain profiles as a function of efficacy of a fungicide program for the control of soybean rust, obtained from 40,000 stochastic simulations. Upper pair of plots (A and B) depict yield gain in kg per hectare for high ($\geq 57.8\%$) and low ($< 57.8\%$) soybean rust severity, while the bottom pair of plots (C and D) depict percent yield gain for the high and low severity. Solid lines represent the median while dashed lines represent the 2.5 and 97.5 percentiles.

For a hypothetical 75% control efficacy, the simulated median of the overall absolute (relative) yield gain was 610.4 kg/ha (29.5%) being ~ 33%, on average, higher or lower than the median for scenarios of higher or lower disease pressure (Table 2).

Table 2: Mean ($\bar{Y}$), median ($Q_{0.5}$), and 0.025 ($Q_{0.025}$) and 0.975 ($Q_{0.975}$) quantiles of the simulated yield gains for overall, high and low severities (57.8% cutoff), and high and low yield (2995.1 kg/ha cutoff), expressed in absolute and relative terms, for an expected 75% control efficacy.

Attainable Yield	Severity	Absolute yield gain (kg/ha)				Relative yield gain (%)			
		$\bar{Y}$	$Q_{0.5}$	$Q_{0.025}$	$Q_{0.975}$	$\bar{Y}$	$Q_{0.5}$	$Q_{0.025}$	$Q_{0.975}$
Overall	Overall	721.2	610.4	71.5	1971.5	98.4	29.5	2.6	505.7
High	High	1097.7	1005.7	252.0	2401.2	113.7	43.7	7.7	545.9
High	Low	529.1	444.4	55.3	1486.6	22.7	14.6	1.6	90.4
Low	High	826.8	768.7	179.4	1769.3	236.4	61.1	8.9	1258.4
Low	Low	429.0	356.2	42.1	1221.0	46.6	20.0	1.9	215.5

Break-even probabilities

Four probability matrices relating fungicide program efficacy and total cost were produced separately for the combinations of each scenario of SBR severity (low and high pressure) and attainable yield (low and high) (Fig. 4). Overall, the frequency of break-even probabilities was higher for situations of

high disease pressure, meaning a lower risk of not recovering the investment (Fig. 4A and Fig. 4C). Similarly, the frequency of break-even probabilities was higher for situations of high attainable yield. For high disease pressure and high attainable yield, the total fungicide costs may exceed US\$270.00/ha when the efficacy is at least 75%, but for low attainable yield, the costs should not exceed US\$210.00/ha. Using less efficacious fungicide programs, assuming a decrease in efficacy to 50%, the total cost should not exceed US\$195.00/ha for high attainable yield (Fig. 4A), and US\$135.00/h for low attainable yield (Fig. 4C).

Figure 4: Probability of break-even event (income $\geq$ costs) conditioned to the efficacy and cost of a fungicide program. Stochastic simulations were performed for scenarios that combined two disease severity level (57.8% cutoff) and yield (2995.1 kg/ha cutoff) (A) high severity and high yield; (B) low severity and high yield; (C) low severity and low yield; and (D) Low severity and low yield.

In a low disease pressure scenario and high yield, total costs with fungicide application should not exceed US\$120.00/ha for an expected 75% efficacy, while for low yield this value is US\$90.00/ha. In scenarios of low efficacy (50%) the total fungicide cost should not exceed US\$75.00/ha (Fig. 4B) for high yield, and US\$60.00/ha for low attainable yield.

Profitability over time

The temporal patterns of the break-even event for two distinct rates of decline in efficacy derived empirically in a previous study are depicted in Fig. 5. For the high annual rate of decline (e.g. TEB), a breakeven event is likely to occur only in the first 5 to 7 years of use (Fig. 5A). For cheaper options, breakeven is very likely to occur (> 0.75) in the first 5 years (Fig. 5A). After five years, breakeven probabilities decrease steeply. For the low rate of decline (e.g. CYPR) break-even events are very likely to occur during the ten years for all programs, but more often for less expensive fungicides (Fig. 5B).

Figure 5: Temporal patterns of the probability of break-even (income $\geq$ costs) events for three fixed costs of two fungicide programs representing a (A) and low (0.061; cyproconazole), and (B) high (0.147; tebuconazole) annual rate of decline determined in a previous study (Dalla Lana et al 2018).

Discussion

The simulation approach used in this study focused on deriving probability matrices for economic decisions based on an expected efficacy of a fungicide program to control soybean rust. Our motivation was based on the current challenge for both industry and soybean growers, which is the design and use of a highly effective and profitable program in a scenario of less

certain efficacy for many fungicides. Hence, we focused on maximising the odds of profit rather than yield response alone. There is a positive relationship between fungicide use (dose or application frequency) and efficacy that may translate into increased yield savings. However, it is not certain whether they are more profitable than low-cost (fewer sprays), though less effective treatments (Beruski et al., 2020). Fungicide programs are complex systems where economical and other factors should be considered and are key to define both the short and long-term benefits from relying heavily on fungicides in disease management.

The presented relationship between efficacy and yield increase is intrinsically dependent on knowledge gathered in previous studies on the soybean rust severity and yield relationship (Dalla Lana et al., 2015). In fact, a positive association between control efficacy and yield response to fungicides has been suggested in flowering diseases of wheat (Machado et al., 2017) and soybean (Barro et al., 2019). For soybean rust, the relationship has been established for many fungicides with varying efficacy and yield response (Dalla Lana et al., 2018). The output of our stochastic simulations is in general agreement with the aforementioned study, e.g. a 49% yield gain was determined for the most effective (79% efficacy) fungicide. The median yield gain simulated for the high "disease pressure" in our study was 53%, which falls within the 95% confidence interval (43.6% to 55.2%) determined empirically (Dalla Lana et al., 2018). However, cognisance must be taken as the damage coefficients were obtained from trials where multiple fungicides have been tested and provided a gradient in disease and yield. Once further research data for specific conditions that alter the damage coefficient significantly (e.g. cultivar susceptibility, biological control, etc) become available the proposed framework is flexible enough to accommodate these changes by updating the parameters.

A similar stochastic simulation approach has been used by Shah and Dillard (2006). The authors obtained meta-analytic estimates of the damage coefficient for sweet corn rust and fitted a uniform probability distribution to the minimum and maximum cost of one spray of strobilurin fungicide to simulate the resulting distribution of severity reduction in treated fields. Consequently, the minimum percent reduction necessary for one spray of strobilurin fungicide to be cost-effective (90% of the time) was determined (5% or 12% reduction for processing or sweet market sweet corn, respectively). In contrast, we focused on the efficacy and cost of a fungicide program as inputs to obtain the portability of breakeven conditioned to two scenarios of disease severity in the untreated condition and high and low-yield production situations. Our finding of break-even events being less

likely in low disease scenarios agrees with other studies that showed greater risks of not-offsetting costs of fungicide sprays to control other diseases of field crops during less severe epidemic conditions and high yields (Paul et al., 2011; Friskop et al., 2018).

Currently, SBR management is based on calendar applications, a non-sustainable model, given the serious issues associated with resistance to fungicides that have arisen from expansive and frequent applications (Godoy et al., 2016; Dalla Lana et al., 2018). The general perception is that the risk of severe damage is always high, which is not true, even in experiments conducted in conditions (late season) that are more favourable for disease (Dalla Lana et al., 2018; Beruski et al., 2020). Concerns with fungicide resistance have influenced decisions during planning fungicide programs, which invariably involved the use of new, usually more costly, commercial fungicides with multiple chemistries, including the addition of protectant fungicides, incrementing the costs (Godoy et al., 2016).

Our stochastic simulation of profitability from fungicide use, based on the expected control efficacy, disease risk, and expected yields, may be useful during planning fungicide usage for soybean rust control considering the total cost of the program. A more general framework could include information on disease risk during the season provided by warning systems that operate at both regional (early season) and field-level (within-season) (Del Ponte et al., 2006; Beruski et al., 2020). Additionally, a farm-level crop model to predict the attainable yield for specific fields could be included. To illustrate, knowing that drought was likely to occur (the case of southern Brazil in the 2020/21 season), a more affordable program (fewer sprays of non-expensive fungicides) could be planned and used based on the expected efficacy for the low disease scenario and lower yields. Indirectly, this is a very important anti-resistance strategy.

The consideration of annual rates of decline in control efficacy linked to economics may be useful for strategic decisions, particularly in the longer term. Our simulations using three fixed total costs and fixed distribution of soybean prices showed how long profitable scenarios can be maintained. In Brazil, soybean prices are volatile and the possibility to define a more realistic price range can improve the value of the simulations. This option is currently implemented in our web application.

Our work highlights the critical role that the nation-wide network of trials for monitoring and updating, via meta-analysis, the performance of individual fungicides and alerting potential issues related to fungicide resistance (Godoy et al., 2016). Although it may be more difficult to obtain a representative sample, due to the high number of fungicides currently used, it

would be instructive to determine the efficacy of fungicide programs (active ingredients, sequence, doses, etc) that is a more realistic situation in commercial production. One of the current limitations of the system is the need for the user to provide an estimate for the more likely efficacy, obtained from reported efficacies that are updated yearly for the most recent year or eventually with multi-year summaries using meta-analysis. Further experimental and modelling studies could be performed to calculate an expected efficacy for multiple fungicides.

The interactive web shiny app (accessible at <https://alvesks.shinyapps.io/rusty-profits>) may be a useful risk analysis tool to aid in strategic pre- and multi-season decisions by researchers, extensionists, and farmers. Future work should focus on updating parameters of the theoretical distributions as new, regional or agronomic-specific, data are gathered, as well as improving the application to connect with other databases and systems to provide a comprehensive risk analysis tool.

Acknowledgments

This study was financed in part by the 'Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil' (CAPES) - Finance Code 001. The second author is thankful to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for providing scholarships. The fourth author received a research fellowship from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)/Brazil.

References

- Barro, J.P., Meyer, M.C., Godoy, C.V., Dias, A.R., et al. (2019) Performance and profitability of fungicides for managing soybean white mold: a 10-year summary of cooperative trials. *Plant Disease*. 103 (9), 2212–2220.
- Beruski, G.C., Del Ponte, E.M., Pereira, André.B., Gleason, M.L., et al. (2020) Performance and profitability of rain-based thresholds for timing fungicide applications in soybean rust control. *Plant Disease*. 104 (10), 2704–2712.
- Brent, K. J. & Hollomon, D. W. (1995) *Fungicide resistance in crop pathogens: how can it be managed?* FRAC Monograph no. 1. 2nd edition. Brussels, GIFAP.
- Chang, W., Cheng, J., Allaire, J.J., Xie, Y., et al. (2020) 01237. shiny: Web Application Framework for R. [Online]. Available from: <https://CRAN.R-project.org/package=shiny>.
- Dalla Lana, F., Paul, P.A., Godoy, C.V., Utiamada, C.M., et al. (2018) Meta-analytic modeling of the decline in performance of fungicides for managing soybean rust

- after a decade of use in Brazil. *Plant Disease*. 102 (4), 807–817.
- Dalla Lana, F., Ziegelmann, P.K., Maia, A. de H.N., Godoy, C.V., et al. (2015) Meta-analysis of the relationship between crop yield and soybean rust severity. *Phytopathology*. 105 (3), 307–315.
- Del Ponte, E.M. & Esker, P.D. (2008) Meteorological factors and Asian soybean rust epidemics: a systems approach and implications for risk assessment. *Scientia Agricola*. 65 (spe), 88–97.
- Del Ponte, E.M., Godoy, C.V., Li, X. & Yang, X.B. (2006) Predicting severity of Asian soybean rust epidemics with empirical rainfall models. *Phytopathology*. 96 (7), 797–803.
- Del Ponte, E.M., Maia, A. de H.N., dos Santos, T.V., Martins, E.J., et al. (2011) Early-season warning of soybean rust regional epidemics using El Niño Southern/Oscillation information. *International Journal of Biometeorology*. 55 (4), 575–583.
- Duffeck, M.R., Alves, K.S., Machado, F.J., Esker, P.D., et al. (2020) Modeling yield losses and fungicide profitability for managing fusarium head blight in Brazilian spring wheat. *Phytopathology*. 110 (2), 370–378.
- Elzhov, T.V., Mullen, K.M., Spiess, A.-N. & Bolker, B. (2016) *minpack.lm: R Interface to the Levenberg-Marquardt Nonlinear Least-Squares Algorithm Found in MINPACK, Plus Support for Bounds*. [Online]. Available from: <https://CRAN.R-project.org/package=minpack.lm>.
- Friskop, A., Yellareddygar, S., Gudmestad, N.C., Fuller, K.B., et al. (2018) Low benefits from fungicide use on hard red wheat in low-disease environments. *Plant Health Progress*. 19 (4), 288–294.
- Godoy, C.V., Bueno, A. de F. & Gazziero, D.L.P. (2015) Brazilian soybean pest management and threats to its sustainability. *Outlooks on Pest Management*. 26 (3), 113–117.
- Godoy, C.V., Seixas, C.D.S., Soares, R.M., Marcelino-Guimarães, F.C., et al. (2016) Asian soybean rust in Brazil: past, present, and future. *Pesquisa Agropecuária Brasileira*. 51 (5), 407–421.
- Klosowski, A.C., Castellar, C., Stammler, G. & May De Mio, L.L. (2018) Fungicide sensitivity and monocyclic parameters related to the *Phakopsora pachyrhizi*-soybean pathosystem from organic and conventional soybean production systems. *Plant Pathology*. 67 (8), 1697–1705.
- Klosowski, A.C., May De Mio, L.L., Miessner, S., Rodrigues, R., et al. (2016) Detection of the F129L mutation in the cytochrome b gene in *Phakopsora pachyrhizi*. *Pest Management Science*. 72 (6), 1211–1215.
- Machado, F.J., Santana, F.M., Lau, D. & Del Ponte, E.M. (2017) Quantitative review of the effects of triazole and benzimidazole fungicides on Fusarium head blight and wheat yield in Brazil. *Plant Disease*. 101 (9), 1633–1641.
- Madden, L.V., Hughes, G. & van den Bosch, F. (2007) *The Study of Plant Disease Epidemics*. Epidemiology. [Online]. St. Paul, APS Press.
- Mendiburu, F. de (2020) 00000. *agricolae: Statistical Procedures for Agricultural Research*. [Online]. Available from: <https://CRAN.R-project.org/package=agricolae>.

- Molina, J.P.E., Paul, P.A., Amorim, L., Silva, L.H.C.P. da, et al. (2019) Meta-analysis of fungicide efficacy on soybean target spot and cost-benefit assessment. *Plant Pathology*. 68 (1), 94-106.
- Paul, P.A., Madden, L.V., Bradley, C.A., Robertson, A.E., et al. (2011) Meta-analysis of yield response of hybrid field corn to foliar fungicides in the U.S. corn belt. *Phytopathology*. 101 (9), 1122-1132.
- Pedersen, T.L. (2020) 00000. *patchwork: The Composer of Plots*. [Online]. Available from: <https://CRAN.R-project.org/package=patchwork>.
- R Core Team (2020) *R: A Language and Environment for Statistical Computing*. [Online]. Vienna, Austria, R Foundation for Statistical Computing. Available from: <https://www.R-project.org/>.
- Roehrig, R., Boller, W., Forcelini, C.A., Chechi, A., et al. (2018) Use of surfactant with different volumes of fungicide application in soybean culture. *Engenharia Agrícola*. 38 (4), 577-589.
- Ross, S. (2013) *Simulation*. 5th edition. [Online]. Elsevier. Available from: doi:10.1016/C2011-0-04574-X
- Scherm, H., Christiano, R.S.C., Esker, P.D., Del Ponte, E.M., et al. (2009) Quantitative review of fungicide efficacy trials for managing soybean rust in Brazil. *Crop Protection*. 28 (9), 774-782.
- Schmitz, H.K., Medeiros, C.-A., Craig, I.R. & Stammers, G. (2013) Sensitivity of *Phakopsora pachyrhizi* towards quinone-oxidoreductase-inhibitors and demethylation-inhibitors, and corresponding resistance mechanisms. *Pest Management Science*. 70 (3), 378-388.
- Shah, D.A. & Dillard, H.R. (2006) Yield loss in sweet corn caused by *Puccinia sorghi*: a meta-analysis. *Plant Disease*. 90 (11), 1413-1418.
- Simões, K., Hawlik, A., Rehfus, A., Gava, F., et al. (2018) First detection of a SDH variant with reduced SDHI sensitivity in *Phakopsora pachyrhizi*. *Journal of Plant Diseases and Protection*. 125 (1), 21-26.
- Wickham, H. (2016) *ggplot2: elegant graphics for data analysis*. Use R! Second edition. Cham, Springer.
- Willbur, J.F., Mitchell, P.D., Fall, M.L., Byrne, A.M., et al. (2019) Meta-analytic and economic approaches for evaluation of pesticide impact on sclerotinia stem rot control and soybean yield in the North Central United States. *Phytopathology*TM. 109 (7), 1157-1170.
- Wise, K.A., Smith, D., Freije, A., Mueller, D.S., et al. (2019) Meta-analysis of yield response of foliar fungicide-treated hybrid corn in the United States and Ontario, Canada. *PLOS ONE*. 14 (6), e0217510.