JHONATAN PAULO BARRO

COMPARATIVE PERFORMANCE AND PROFITABILITY OF FUNGICIDES FOR MANAGING SOYBEAN WHITE MOLD: A NETWORK META-ANALYSIS

Dissertação apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Fitopatologia, para obtenção do título de *Magister Scientia*e.

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APROVADA: 23 de julho de 2018.

Eduardo Seiti Gomide Mizubuti

S Pethybridge
Sarah Pethybridge

Emerson Medeiros Del Ponte
(Orientador)

Aos meus amados pais, Clecir e Claudecir

À minha querida irmã, Caislene

Aos meus familiares e amigos que sempre torceram por mim

***DEDICO**!*

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BIOGRAFIA

JHONATAN PAULO BARRO, filho de Clecir Fátima Barro e Claudecir José Barro, nasceu em Jacutinga, Rio Grande do Sul, em 25 de novembro de 1991.

Em março de 2010, ingressou no curso de Agronomia na Universidade Federal Fronteira Sul - UFFS, Campus Erechim, RS. Realizou um intercâmbio de agosto de 2013 a dezembro de 2014 na Kansas State University sendo bolsista CAPES no programa “Ciências sem Fronteiras”. Graduou em março de 2017.

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SUMÁRIO

ABSTRACT

BARRO, Jhonatan Paulo, M.Sc., Universidade Federal de Viçosa, July, 2018. **Comparative performance and profitability of fungicides for managing soybean white mold: a network meta-analysis**. Adviser: Emerson Medeiros Del Ponte.

White mold, caused by the fungus *Sclerotinia sclerotiorum* and also known as Sclerotinia stem rot, is a damaging disease of worldwide importance to several crops including soybean. Fungicides are recommended for the control of white mold in Brazil but the best options and the economic benefits have not been fully explored. The data were obtained from a national cooperative trial network conducted from 2008 to 2017 across 23 locations in Brazil, totaling 72 trials. The five fungicide treatments evaluated in at least 20 trials during four years, and applied twice (flowering - R1 and 10 days later), were: dimoxistrobin+boscalid (DIMO+BOSC), fluazinam (FLUZ), fluopyram (FLUO), procymidone (PROC) and carbendazim+procymidone (CARB+PROC). The sixth treatment was the benzimidazole thiophanate-methyl (TIOF) applied four times starting at R1 stage and every 10-day interval, which was available in 43 trials conducted during seven growing seasons. A network meta-analytic model was fitted to the log of the means of white mold incidence (%) and sclerotia mass (g/ha) data and to the non-transformed mean yield (kg/ha) for each treatment, including the control. The estimated percent reduction in disease incidence relative to the control ranged from 55.2% (TIOF) to 82.8% (CARB+PROC); the latter not differing from FLUO (80.8%) and DIMO+BOSC (80.8%). There was similar percent reduction in sclerotia mass for CARB+PROC (86.4%), DIMO+BOSC (84.9%) and FLUO (83.0%), all performing better than TIOF (53.9%). The mean yield gain ranged from 312 kg/ha (TIOF) to 593 kg/ha (FLUZ); the latter did not differ from DIMO+BOSC (588 kg/ha) and FLUO (551 kg/ha). The model was expanded to include a moderator variable for the incidence level in the check treatment, or the baseline incidence (≤30% or >30%) that explained portion of the heterogeneity. The mean estimates and between-study variance for each baseline disease class were used to calculate the probability of breaking even on fungicide costs. Different scenarios of soybean prices (252 to 404 U$/ton) and fungicide costs (product + application) were created. For TIOF, the range was from 52 to 84 U$/ha (for four applications); for FLUZ, DIMO+BOSC and CARB+PROC the range was from 80 to 112 U$/ha (two applications);

and for PROC the range was from 70 to 102 U$/ha (two applications). For the high-disease scenario, probabilities were higher (> 65%) for the more effective/expensive fungicides. For the low-disease scenario, profitability depended on the benefit-cost ratio of fungicides. These results may be useful for decision making in disease management by taking both technical and economic decisions into account.

RESUMO

BARRO, Jhonatan Paulo, M.Sc., Universidade Federal de Viçosa, julho de 2018. **Desempenho comparativo e rentabilidade de fungicidas no manejo do mofo branco da soja: uma metanálise em rede**. Orientador: Emerson Medeiros Del Ponte.

Mofo branco, causado pelo fungo *Sclerotinia sclerotiorum* e também conhecido como podridão branca da haste, é uma doença que causa perdas em várias culturas pelo mundo, incluindo a soja. Alguns fungicidas são recomendados para o controle de mofo branco no Brasil, mas as melhores opções e os benefícios econômicos não têm sido totalmente explorados. Os dados foram obtidos de uma rede de ensaios cooperativos conduzidos de 2008 a 2017 em 23 localidades no Brasil, totalizando 72 ensaios. Os 5 fungicidas avaliados em ao menos 20 ensaios durante quatro safras e aplicados duas vezes (R1 e 10 dias depois) foram: dimoxistrobina + boscalida (DIMO+BOSC), fluazinam (FLUZ), fluopyram (FLUO), procimidona (PROC), e carbendazim+procimidona (CARB+PROC). O sexto tratamento foi Tiofanato metílico (TIOF) aplicado quatro vezes, R1 e a cada 10 dias de intervalo entre aplicações, avaliável em ao menos 43 ensaios conduzidos em sete safras. Modelos de metanálise em rede foram ajustados para o log das médias de incidência (%) e massa de escleródios (g/ha) e para os dados médios não transformados de produtividade (kg/ha) para cada tratamento, incluindo a testemunha. A redução de incidência da doença relativa à testemunha variou de 55.2% (TIOF) a 82.8% (CARB+PROC); sendo que CARB+PROC não diferenciou de FLUO (80.8%) e DIMO+BOSC (80.8%). A redução da massa de escleródios foi similar para CARB+PROC (86.4%), DIMO+BOSC (84.9%) e FLUO (83.0%), todos melhores que TIOF (53.9%). As médias em ganho de produtividade variaram de 312 kg/ha (TIOF) a 593 kg/ha (FLUZ), sendo que FLUZ não diferenciou de DIMO+BOSC (588 kg/ha) e FLUO (551 kg/ha). O modelo foi expandido para incluir uma variável moderadora para níveis de incidência (>30% e <30%) que explicou parte da heterogeneidade. As estimativas metanalíticas e a respectiva variância para cada nível de incidência foram usadas para calcular a probabilidade de compensar o custo do controle. Foram criados diferentes cenários de preços de soja (252 a 404 U$/ton) e custo de fungicidas. Para TIOF a variação foi de 52 a 84 U$/ha (quatro aplicações); para FLUZ, DIMO+BOSC e CARB+PROC a variação foi de 80 a 112 U$/ha (duas aplicações); e para PROC a variação foi de 70 a 102 U$/ha (duas aplicações). Para cenários de alta incidência, probabilidades foram maiores (> 65%) para os fungicidas mais eficazes/caros. Para cenários de baixa incidência, a rentabilidade depende da relação custo-benefício do uso dos fungicidas. Esses resultados podem ser úteis para a tomada de decisões no manejo de doenças, levando em consideração tanto as decisões técnicas quanto as econômicas.

INTRODUCTION

White mold, also known as Sclerotinia stem rot, is a damaging disease of worldwide importance for several crops including soybean, canola, cotton, beans, potato and sunflower (Boland and Hall 1994). Symptoms of the disease include water-soaked stem lesions that acquire light brown coloration resulting in the appearance of dense white mycelium - hence the name "white mold". Severely infected plants may wilt and die prematurely (Peltier et al. 2012). In Brazil, soybean yield losses due to white mold may reach 70%, and the epidemics have been more commonly reported at high elevation regions (> 600m) where cooler conditions favors the disease (Meyer et al. 2014; Lehner et al. 2016; Meyer et al. 2016). The disease is endemic to approximately 23% (7.7 millions hectares) of soybean production area in Brazil (Meyer et al. 2016). In the United States, losses due to white mold from 1996 through 2009 were estimated to increase from 10 to 560 million U$, ranking the disease as the second most important for soybean (Peltier et al. 2012). In addition to causing yield loss, white mold affects seed germination and soybean quality by reducing oil and protein concentrations in grains (Hoffman et al. 1998; Danielson et al. 2004).

White mold is caused by *Sclerotinia sclerotiorum*, an ascomycete that is capable of surviving and remaining viable for several years in soil in the form of sclerotium, a hard dark resting body constituted of a mass of hyphal threads (Adams and Ayers 1979). During moist periods and cooler temperatures (10 to 21°C), sclerotia germinate and produce multiple apothecia - over two million ascospores can be produced in a single apothecium (Schwartz and Steadman 1978; Adams and Ayers 1979; Clarkson et al. 2014). These ascospores (primary inoculum) are discharged from the apothecia and dispersed within the canopy by air currents. When reaching the flowers, they are capable of infecting the petals when the weather conditions are right, such as temperature between 15 - 25°C and leaf wetness of 2-4 hours (Young et al. 2004). The infected senescing flowers provide a nutrient source for the fungus to infect the stem and leaves, after petal fall, and produce abundant white mycelia that will further turn into dark sclerotia of variable sizes (Abawi and Grogan 1975; Boland and Hall 1994; Lehner et al. 2016; Fall et al. 2018).

A dense plant canopy during flowering (R1 stage) through the beginning of pod formation (R3 stage) favors disease development by creating a cooler and moist environment due to rain and dew. The disease may spread from one field to another by windblown ascospores, or by soil adhering to soybean seedlings, farm equipment or animals, in the form of sclerotia or as mycelium in infected host tissue (Peltier et al. 2012). Overhead irrigation favors disease spread as the sclerotia are able to remain viable for at least 10-21 days in flowing water (Schwartz and Steadman 1978). Long distance dispersal occurs via mycelium-infected seed or sclerotia-infested seed lots (Adams and Ayers 1979).

The disease is best managed by integrating multiple tactics. As the fungus has a wide host range, including many broadleaf crops and weeds, rotating with grasses is one way to reduce its inoculum (Mueller et al. 2002). In addition, modifying row spacing (Vieira et al. 2010), seed density (Teixeira et al. 2013) and time of sowing help to avoid a dense canopy, which is favored by early planting, narrow row width, high plant populations, and high soil fertility (Peltier et al. 2012). Least susceptible cultivars should be preferred, since complete resistance is not available. Cultivars with an architecture that allows better aeration between plants (little branched and with small leaves) and with shorter period of flowering may help to disease avoidance. The use of healthy/treated seeds prevents introduction of inoculum into the field (Peltier et al. 2012; Meyer et al. 2014).

Biological control had long been proposed to integrate to disease management, mainly targeting sclerotia on the soil surface using biocontrol agents (BCAs) antagonists such as fungi (e.g. *Trichoderma* spp.) and bacteria (*Bacillus* spp.) (Adams and Ayers 1979). The application of BCAs should be made prior to sclerotia germination, when they are resting at the soil surface (Meyer et al. 2014). Alternatively, the use of herbicides containing lactofen has proven effective against the disease. These herbicides can induce a systemic resistance response that increases phytoalexin production by the soybean plant, an antimicrobial that can inhibit *S. sclerotiorum* growth (Landini et al. 2003; Peltier et al. 2012).

Besides all those tactics, chemical control remains the most effective method for protecting soybean plants during the flowering period against ascosporic infection (Muller et al. 2002; Sumida et al. 2015; Cardoso et al. 2015; Meyer et al. 2016; Wutzki et al. 2016). Fungicide applications are also key for controlling the disease in other crops such as dry beans (Mahoney et al. 2014; McCreary et al. 2016; Miorini et al. 2017), rapeseed (Liang et al. 2015; Hou et al. 2017) and carrots (McDonald et al. 2008).

In Brazil, several active ingredients have been tested and proven effective at various levels for the control of white mold including fluazinam (inhibitor of phosphorylation oxidative, acting on the respiration of the pathogen), procymidone (acts on osmoregulation of the fungal membranes), thiophanate-methyl (inhibits mitotic division by disturbing the assemblage of microtubules) and boscalid (inhibitor of succinate dehydrogenase, which acts in stage II of fungus respiration) (Brent and Hollomon 2007; Meyer et al. 2014; Meyer et al. 2017). In New York state (United States), fluazinam, boscalid and thiophanate-methyl are commonly used for white mold management in snap beans but relatively lower efficacy has been reported for thiophanate-methyl in field experiments (Lehner et al. 2017).

The number and timing of fungicide application seems critical to improve disease control (Peltier et al. 2012). Mueller et al. (2004) found that fungicides applied as early as beginning of flowering improved control efficacy compared to later applications at beginning of pod formation in the midwestern U.S. The number of applications required seems to vary with the active ingredient used. However, two sprays may be used regularly for an extended protection. However, depending on disease risk, three or four applications of fungicides with different modes of action may be needed (Cardoso et al. 2015; Wutzki et al. 2016; Miorini et al. 2017).

Regarding application technology, foliar fungicides should reach the bottom canopy for increased efficacy. Flat fan spray nozzles that produce high-fine to mid-medium droplets (200–400 μm) provides better coverage of soybean plants (Peltier et al. 2012; Berger Neto et al. 2017).

The downside of the dependence on fungicides, mainly those with site-specific mode of action, is the risk of resistance to fungicides in the pathogen population (Ma and Michailides 2005; Avenot and Michailides 2010). The resistance to benzimidazoles such as thiophanate-methyl, largely used by Brazilian growers, has been reported in field populations of many other plant pathogens (Koenraadt et al. 1992). Resistance to fluazinam, a fungicide with a multi-site mode of action, has not been yet reported for *S.*

sclerotiorum in a survey conducted in Brazil, but one strain resistant to thiophanate-methyl was found recently (Lehner et al. 2015). Resistance to dicarboxamide such as dimethachlon was reported in *S. sclerotiorum* field isolates (Zhou et al. 2014). Resistance to procymidone has not yet been reported in field, but resistant isolates were obtained in the laboratory (Liu et al. 2010). Thus, to minimize the risk of fungicide resistance and extend the lifetime of fungicides, best practices have been recommended by FRAC (Fungicide resistance action committee), including use of fungicides in mixture or in rotation, restrict the number of treatments applied per season, and apply the recommended dose (Van den Bosch et al. 2014; Elderfield et al. 2018).

In Brazil, a range of fungicides with varying modes of action has been evaluated and their performance (disease reduction and yield increase) is variable among them and within a same fungicide across trials (Meyer et al. 2014). A cooperative trial network has been established in the country since the year 2008 to evaluate the efficacy of fungicides against white mold. However, the best options and the economic benefits from using different fungicides have not been fully explored for these datasets using a modeling framework that combine all available evidence. A previous study summarized the performance, yield benefits and economics of only one fungicide (fluazinam) evaluated in several trials conducted in the state of Paraná State and used a different data source (Tupich et al. 2017).

In this study we aimed to summarize and compare the performance of fungicides with known and variable effect on disease reduction which were selected based on knowledge of the primary studies. For such, we used a meta-analysis, a technique that combine statistics of the treatment of interest (means and variance) obtained from primary studies to summarize an effect-size (e.g. average yield gain) and identify factors that could explain portion of heterogeneity (Madden et al. 2016). This method has gained popularity to summarize fungicide performance in plant disease management (Paul et al. 2008; Huang et al. 2012; Belova et al. 2013; Salam et al. 2013; Machado et al. 2017). When multiple comparisons among treatments are of interest, network meta-analysis (NMA) has been recommended as a more powerful approach to overcome the limitations of the traditional pairwise meta-analyses which are restricted to compare only two treatments at a time and do not take the within-study correlations into account (Madden et al. 2016).

Originally developed to use data generated from trials with two arms and with a common comparator, thus allowing the indirect comparison of three treatments (A vs. B; B vs. C), NMA involves more than one common comparator (the linking treatment) that allows simultaneously both direct and indirect results from all studie’s arms into a single pooled effect (Lumley 2002; Lu and Ades 2004; Salanti et al. 2008; Lu and Ades 2009; Zhang et al. 2014). The most common approach to NMA in plant pathology, is the arm-based modeling, also known as unconditional model, where treatment means and not the contrasts are used as effect-sizes (Madden et al. 2016). Several studies have fitted network models to fungicide trial data to obtain estimates of disease control efficacy and yield response (Paul et al. 2008; Ngugi et al. 2011; Madden et al. 2016; Machado et al. 2017).

In this study we estimated the relative reduction (percent control efficacy) of white mold disease incidence and sclerotia production, as well as yield response to the application of a set of fungicides evaluated during nine growing seasons and across several locations in Brazil. The economics were explored using the mean and respective between-study variances of the meta-analytic estimates of yield response to calculate the probability of breaking-even on costs for a range of scenarios of soybean prices and fungicide costs.

MATERIAL AND METHODS

Data and experimental procedures

The database of soybean yield and disease (white mold incidence and sclerotia mass) were obtained from a national cooperative trial network ("Ensaios Cooperativos"). These trials were firstly established ten years ago (2008) for evaluating the performance of fungicides against soybean white mold. Most of the data used in our study have been published as yearly summaries where a combined analysis approach was used for comparing means (multiple comparison) of white mold incidence (percent of diseased plants), sclerotia mass (g) and soybean yield (kg/ha) across all evaluated fungicides within the year. These reports were made for trials conducted in 2013/14 (Meyer et al. 2015), 2014/15 (Meyer et al. 2015), 2015/16 (Meyer et al. 2016) and 2016/17 (Meyer et al. 2017) growing seasons. The data from 2012/13 were not published (Meyer et al. personal communication) and data from the 2008/09 to 2011/12 seasons were available at the trial level (multiple comparison made within a trial) in an earlier four-season summary report (Meyer et al. 2014). Data from this latter study has been used in a previous meta-analysis of the disease incidence-soybean yield relationship (Lehner et al. 2016).

The cooperative trials were conducted following a standard protocol as described elsewhere (Lehner et al., 2016). Briefly, the fungicides were applied two, three or four times using a backpack sprayer pressurized by CO_2 with a spray volume of 150-200 L ha^{-1}. The first application occurred between R1 and R2 growth stages with subsequent applications at a fixed 10-day interval. The experimental design was a randomized complete block with four replications (plot was 6m long x 4 rows wide), including a nontreated control. Disease incidence was quantified between R5 and R6 growth stage as the percentage of diseased plants among all plants within the two central rows of each plot. Sclerotia mass was weighed after threshing all plants from a single plot and expressed to g/ha. Crop yield was calculated and expressed as kg/ha at 13% seed moisture content.

Criteria for treatment selection

We selected five fungicide treatments applied two times (early flowering [R1/R2] and 10 days later) for controlling soybean white mold (Table 1). To be included in the analysis, a fungicide treatment should be tested in at least 20 trials and during four years. The sixth treatment was the benzimidazole Thiophanate-methyl, but applied four times starting at early flowering and every 10-day intervals. This only four-spray treatment, available in 43 trials conducted during seven growing seasons, was included due to being a more cost-effective fungicide compared to the others, and is usually applied more than twice. Complete information for the selected fungicide treatments are described in Table 1.

After treatment selection, the database, with raw data at the plot (block) level (four replicates) comprised 72 independent trials conducted at 23 locations across nine

Brazilian states (Table S1). The states were split into Northern (n = 44 trials, MS, MT, MG, GO and BA) and Southern region (n = 28 trials, SP, PR, and RS) (Figure 1). In the Northern region, most of the trials were conducted in the state of Goiás (n = 27 trials). In the south, most trials were conducted in the state of Paraná (n = 24 trials) which, together with Goiás, accounted for 70.8% of all trials. Across the nine years, most of the trials (n = 14) were conducted during the 2011/12 crop season, followed by 2015/16 (n = 11).

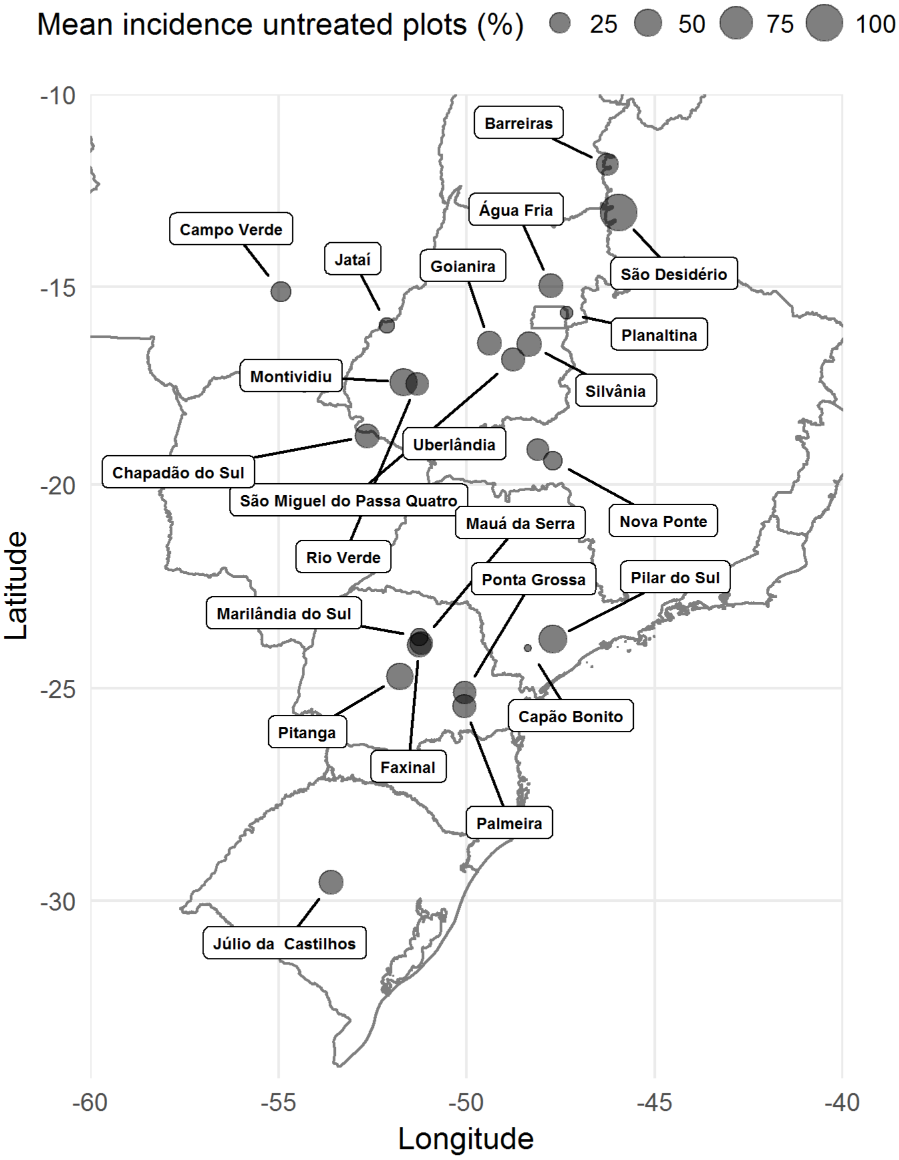


Figure 1: Geolocation of the 23 municipalities across nine states of Brazil where 72 fungicide evaluation trials were conducted and white mold incidence, sclerotia mass production and soybean yield were recorded. The size of the circle is proportional to the mean incidence in the nontreated check plot across trials and years.

Table 1: Six fungicide active ingredients (a.i.) evaluated for the control white mold on soybean in 72 cooperative fungicide trials conducted from 2008/9 to 2016/17 in Brazil.

Fungicide a.i.	Study code	Commercial name	Sprays[a]	FRAC[b]	dose [c]
Dimoxystrobin+Boscalid	DIMO+BOSC	Spot	2	11 + 7	0.4
Fluazinam	FLUZ	Frowncide	2	29	0.5
Fluopyram	FLUO	PNR* + Aureo**	2	7	0.2
Procymidone	PROC	Sumilex	2	2	0.5
Carbendazim+Procymidone	CARB+PROC	Carbomax + Sialex	2	1+2	0.5 + 0.5
Thiophanate-methyl	TIOF	Cercobin	4	1	0.5

[a] number of applications: first spray at flowering and the following 10 days apart; [b] Fungicide Resistance Action Committee (FRAC) code; [c] Dose (g/ha) of the active ingredients for each fungicide; *PNR = Product Not Registered; **Adjuvant.

The number of trials varied across the response variables given that some responses were missing in the trials, such as sclerotia production, not evaluated in 19 trials, and soybean yield not evaluated in only one trial. Therefore, data from all 72 trials were used for the analysis of incidence reduction, from 53 trials for the analysis of reduction in sclerotia production and from 71 trials for the analysis of yield.

Five different trial designs (a specific set of treatments evaluated within a same trial) were found for yield analysis, six for disease incidence and seven for sclerotia production. These designs composed a network of treatments where both direct and indirect evidence of comparison are used in the network meta-analyses. A network graph is composed of nodes (fungicide treatments) and edges or links between two treatments directly compared in a same trial. This graph allows to visualize how the treatments relate to each other and the number of direct comparisons can be depicted by the thickness of the edges, but also with numbers presented at the top of the links. An example of such network graph is shown for the meta-analysis of yield in our study (Figure 2).

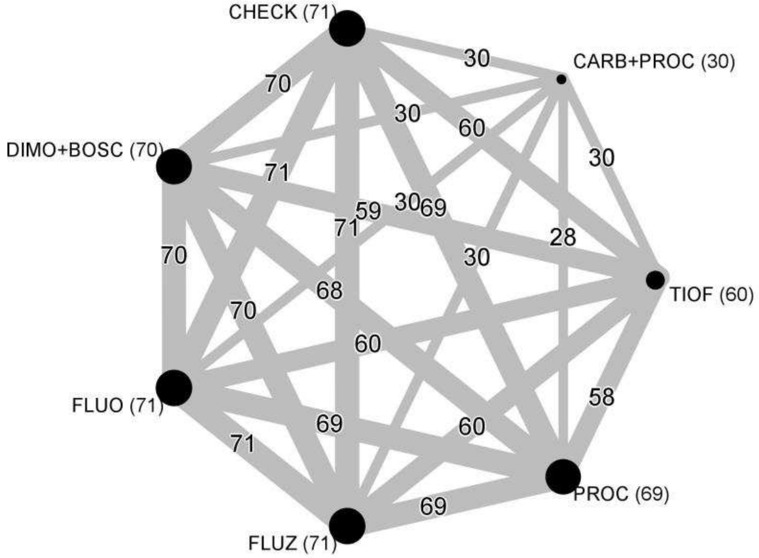


Figure 2: Network of co-occurrences of treatments in 71 trials for estimating differences in soybean yield conducted in Brazil from 2008/9 to 2016/17. Five fungicides (FLUO = fluopyran; FLUZ = fluazinam; PROC = procymidone; DIMO + BOSC = dimoxistrobin + boscalid and CARB + PROC = carbendazim + procymidone) were applied twice and one applied four times (TIOF: tiophanate-methyil). Width of the lines is proportional to the co-occurrences for each two treatment combination. Size of every circle are proportional to the number of trials (within parenthesis).

Response variables

Although data were available at the plot level for most trials, an aggregated measure, the means of the treatment (for each variable of interest) at the trial level, was obtained, which is a typical approach used in meta-analysis (Madden et al. 2016). In this case, a measure of within-study variability is needed and used as a weight, usually the inverse of the sampling variance, where more weight is given for studies with lower sampling variance. Given the availability of data at the plot (block) level, the required within-study sampling variance was obtained from calculating the standard deviation of the four replicates. When raw data is not available, the mean square error of an anova model fitted to the trial data is used as surrogate, but this was not the case in our study (Paul et al. 2008; Machado et al. 2017).

The main variable of interest in our study was the yield response, or the difference or gain from using the fungicides relative to untreated control. Since yield response to fungicides are related to fungicide efficacy (percent disease reduction), we fitted meta-analytic models to estimate mean percent reduction of incidence and sclerotia mass by the selected fungicides.

Meta-analytic model

The mean absolute difference in yield was used as effect size with no transformation required given the statistical properties of the data (Figure 1S). The difference was calculated directly after model fitting by subtracting estimated means for the treatments under comparison (fungicide minus untreated) (Machado et al. 2017). For the disease ratio variables (relative reduction of incidence and sclerotia mass) the log of the means (L_{INC} and L_{SCL}) were used given its better statistical properties than the ratio (Madden et al. 2016) (see Fig1S). The relative estimate was obtained by taking the difference of the estimated means of the logs ($\bar{L}_{INC}$ or $\bar{L}_{SCL}$), which equals the ratio of the two means. The mean ratio was used to calculate the control efficacy ($\bar{C}$, percent reduction in the incidence or sclerotia mass) and their confidence intervals (CI) by back-transforming mean estimates of the ratio (difference in the logs) and the respective upper and lower limits of their CIs as $\bar{C}$= (1 - (exp($\bar{L}_{INC/SCL}$)) × 100) (Paul et al. 2009; Machado et al. 2017). The model can be written as Equation 1:

$$\boldsymbol{Y_i} \sim N(\mu, \sum + \boldsymbol{S_i}) \tag{1}$$

Where $\boldsymbol{Y_i}$ is the vector of L (log of the means of incidence or sclerotia mass) or mean yield for the six treatments plus the nontreated control for the ith study, μ is a vector representing the mean of Y_i across all trials, $\sum$ is a 7 x 7 between-study variance-covariance matrix (for the seven treatments, including the check), and $\boldsymbol{S_i}$ is within-study variance-covariance matrix for the *i*th study. An unstructured $\sum$ matrix (N) was used, given its better fit to the data when comparing to simplex structures such as compound symmetry and heterogeneous compound symmetry (data not shown). N indicates a multivariate normal distribution. The models were fitted to the data with a maximum-likelihood parameter estimation using the *metafor* package (Viechtbauer 2010) of R as described in a previous study (Machado et al. 2017).

Effect of baseline incidence on yield response

The arm-based was expanded to include a moderator variable that could explain, at least in part, the heterogeneity. We created a moderator variable for the incidence level in the check treatment, or the baseline incidence. The yield response from using fungicides usually vary with baseline incidence: the greater the baseline disease, the greater the response, as demonstrated for previous meta-analysis of foliar diseases of maize and target leaf spot of soybean (Paul et al. 2011; Edwards-Molina et al. 2018). For white mold, incidence was shown to be strongly associated with yield loss (Lehner et al. 2016). For simplified scenarios representing low-disease and high-disease "pressure", we splitted the data into two sets of epidemics greater and equal or lower than 30% incidence, the median value encountered in the non-treated plots of our data. The moderator variable was included and tested in the model as interaction term as described elsewhere (Machado et al. 2017).

Effect of trial design on network results

To test for the inconsistency of the network, or whether results are influenced by the study design, each trial was categorized according to its design. In total, six different designs were tested for incidence, seven for sclerotia mass and five for yield data. A factorial-type of anova model was used to test for the significant interaction of the treatment and design, which was evaluated based on the Wald test statistic. The null hypothesis is that the network is consistent (Piepho et al. 2014; Madden et al. 2016).

Probability of breaking-even on fungicide cost

The probability of breaking-even on the fungicide plus application cost (F_C) was calculated using the between-study variance ($\hat{\tau}$) and the mean yield difference ($\overline{D}$) relative to the check treatment estimated by the arm-based meta-analytic models. This probability was calculated as $p = \phi[(\overline{D} - S_P/F_C)/\sqrt{\hat{\tau}}]$, where ϕ is the cumulative standard-normal function (Paul et al. 2011; Machado et al. 2017).

Different scenarios of soybean prices (S_P) and fungicide costs (F_C) (product + application) were created for calculating the probability of breaking-even on the overall costs for all fungicides but fluopyram which is not registered. Average prices of the fungicides considering an exchange rate of \$3.30 BRL = 1 U\$ during March 2018 and fungicide price of 2017/18 crop season were: FLUZ: 40.00 U\$/ha, DIMO+BOSC: 38.00 U\$/ha, PROC: 33.00 U\$/ha, CARB+PROC: 40.00 U\$/ha and TIOF: 7.5 U\$/ha. The operational costs were fixated at 10.00 U\$/ha and the average soybean price used was 378 U\$/ton.

The probabilities were calculated for a range of five fixed values of costs of the fungicide applications and four fixed values of soybean price (252 to 404 U\$/ton). For TIOF, the range was from 52 to 84 U\$/ha (for four applications); for FLUZ, DIMO+BOSC and CARB+PROC the range was from 80 to 112 U\$/ha (two applications); and for PROC the range was from 70 to 102 U\$/ha (two applications). A heatmap of the probability of breaking even on fungicide costs was produced for all combinations of fungicide and soybean prices. The estimates of $\overline{D}$ were calculated for each disease scenario based on results of the expanded meta-analytic model. In addition, line plots were made for depicting probabilities of breaking even for each fungicide across the range of benefit-cost ratio (S_P/F_C) scenarios calculated based on the defined monetary values.

RESULTS

Epidemics in the non-treated and fungicide-treated plots

The trials were typically conducted in locations with historical occurrence of the disease (availability of inoculum), which resulted in white mold detected in all trials. Disease incidence in the non-treated check plots ranged from 3.6 to 100% (median = 30.1%).

Sclerotia were found after harvesting the plots at various amounts, with a median value of 2,626 g/ha, ranging from 40.12 to 14.95 g/ha across the 53 trials.

There was large variation in white mold incidence among the years and within a year, which reflects field-specific differences in initial inocula and weather conditions (data not available). The highest seasonal median incidence (65%) was recorded in the 2008/09 season and the lowest median incidence (14.7%) in the 2012/13 season. On the other hand, sclerotia production was less variable among the years, with the highest amounts in 2012/13 (median = 6,729.6 g/ha) and the lowest amounts in 2015/16 (median = 1,146.8 g/ha) crop seasons (Figure 3B).

As expected, the use of any of the fungicides resulted in reduced levels of white mold incidence and sclerotia production overall compared to the non-treated check. Median levels of incidence and sclerotia mass were mostly below 12% and 1,000 g/ha, respectively when using the fungicides (Figure 4).

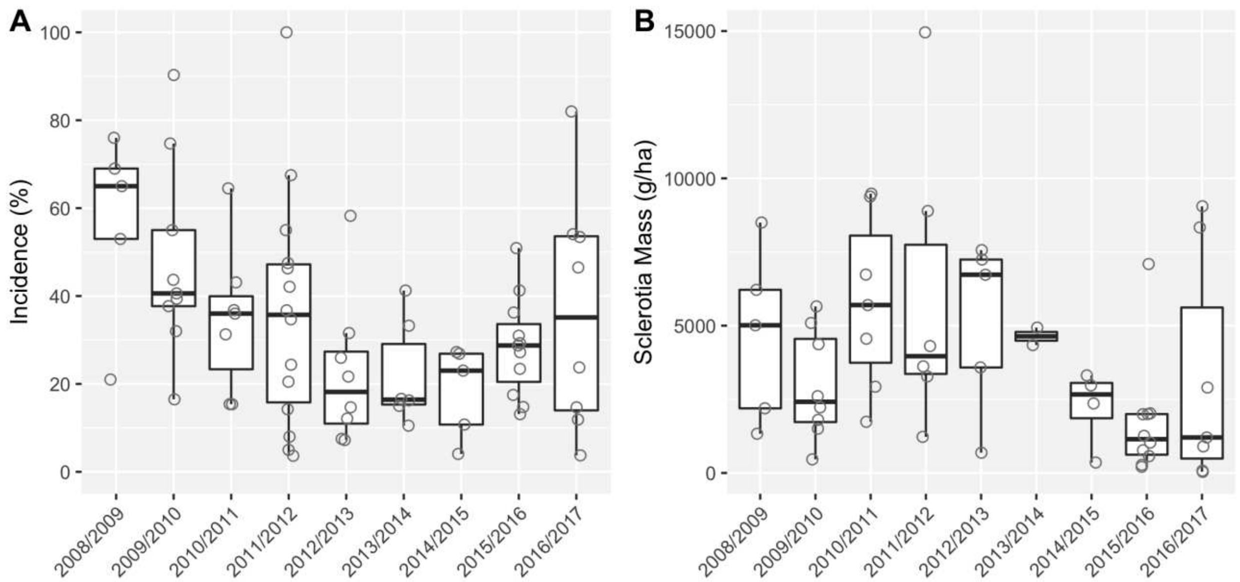


Figure 3: Boxplots for the within-season variation (across trials) of mean white mold incidence (**A**) and sclerotia mass (**B**) in the untreated check of 72 fungicide trials conducted in Brazil from 2008/9 to 2016/17. The thick horizontal line inside the box represents the median, the limits of the box represent the lower and upper quartiles, and the circles represents trial means.

Meta-analysis of disease control

The estimated levels of percent control efficacy for incidence ($\bar{C}_{INC}$)**,** obtained from back-transforming the estimated differences of the logs between a fungicide treatment and the check, varied from 55 to 82%. Three fungicides, CARB+PROC, DIMO+BOSC and FLUO reduced incidence by at least 80% and did not differ significantly among them ($P > 0.3$). These were followed by FLUZ and PROC with efficacies above 72% that differed significantly ($P < 0.05$) only from CARB+PROC. The lowest efficacy was estimated for TIOF (55%), differed significantly from all other fungicides ($P < 0.0001$). The difference in control efficacy between the most and least effective fungicide was 25.61 percentage points (Table 2). The Wald test for the treatment x design interaction showed that the network was consistent ($P = 0.70$).

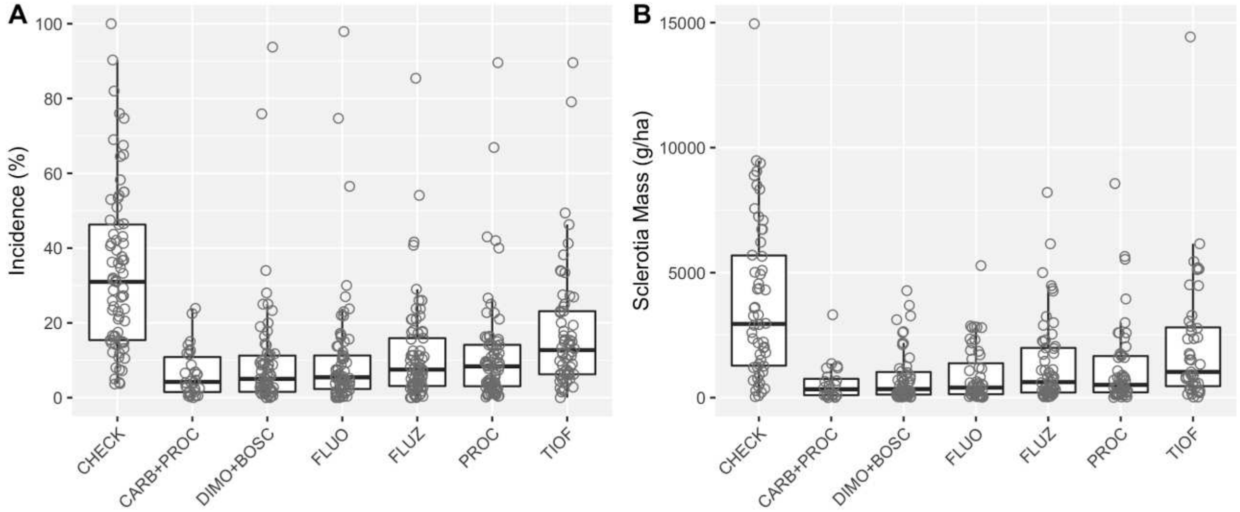


Figure 4: Box plots and individual means of white mold incidence (%) (**A**) and sclerotia mass production (g/ha) (**B**). The treatments consisted of a nontreated check (CHECK) or treated with two sprays of dimoxystrobin+boscalid (DIMO+BOSC), fluazinam (FLUZ), fluopyram (FLUO), procymidone (PROC), carbendazim + procymidone (CARB+PROC), and thiophanate-methyl (TIOF) applied four times. The line inside the box represents the median and the circles represents each treatment mean.

For sclerotia mass reduction, the estimated mean control efficacy relative to non-treated plots ($\bar{C}_{SCL}$), obtained from back-transforming the differences in the logs between a fungicide treatment and the check, varied from 53 to 86%. Three fungicides, CARB+PROC, DIMO+BOSC and FLUO showed percent incidence reduction levels above 80%, followed by FLUZ and PROC with lower efficacy but above 72%. Again, the lowest efficacy was estimated for TIOF (53%), differing significantly from all other fungicides ($P < 0.0001$). The highest efficacy was estimated for CARB+PROC, differing significantly from the three fungicides with efficacies estimated below 80% ($P < 0.05$), but not from the other two with closer values (*P* > 0.3). The difference between the most and least effective was 32.51% for percent reduction in sclerotia mass (Table 2). The Wald test showed that the consistency of the network was affected by the design of the trials (*P* = 0.0001).

There was an association between the estimated efficacies for the two disease variables, although differences between some of them are not too large. In general, the pattern was similar between the two variables with CARB+PROC and TIOF being the most and least effective for reducing both white mold incidence and sclerotia mass (Figure 5).

Table 2: Overall means of control efficacy (percent reduction) of white mold incidence ($\bar{C}_{INC}$[%]) and sclerotia mass ($\bar{C}_{SCL}$[%]) by fungicides evaluated during nine years (2008/9 to 2016/17) across 72 field trials. The means of incidence (percent diseased plants at R5-R6 stage) and sclerotia mass per plot (g/ha), and respective confidence intervals, were estimated by an arm-based meta-analytic model fitted to the log of the treatment means weighted by the inverse of the sampling variance.

	Incidence reduction (%)				Sclerotia mass reduction (%)			
Fungicide[a]	*k*[b]	$\bar{C}_{INC}$	CI_L[c]	CI_U[c]	*k*[b]	$\bar{C}_{SCL}$	CI_L[c]	CI_U[c]
DIMO+BOSC	70	80.8	77.2	83.8	51	84.9	80.7	88.2
FLUZ	71	77.8	74.1	81.0	51	75.7	69.4	80.7
CARB+PROC	30	82.8	77.8	86.6	23	86.4	79.7	90.8
FLUO	71	80.8	76.9	84.1	51	83.0	79.2	86.2
PROC	69	73.8	69.5	77.5	53	77.2	71.0	82.0
TIOF	60	55.2	50.4	59.5	43	53.9	45.4	61.0

[a] See Table 1 for complete information of the evaluated fungicides; [b] number of trials that each fungicide was evaluated; [c] upper (**CI$_U$**) and lower (**CI$_L$**) limits of the 95% confidence interval around $\bar{C}_{INC}$ and $\bar{C}_{SCL}$.

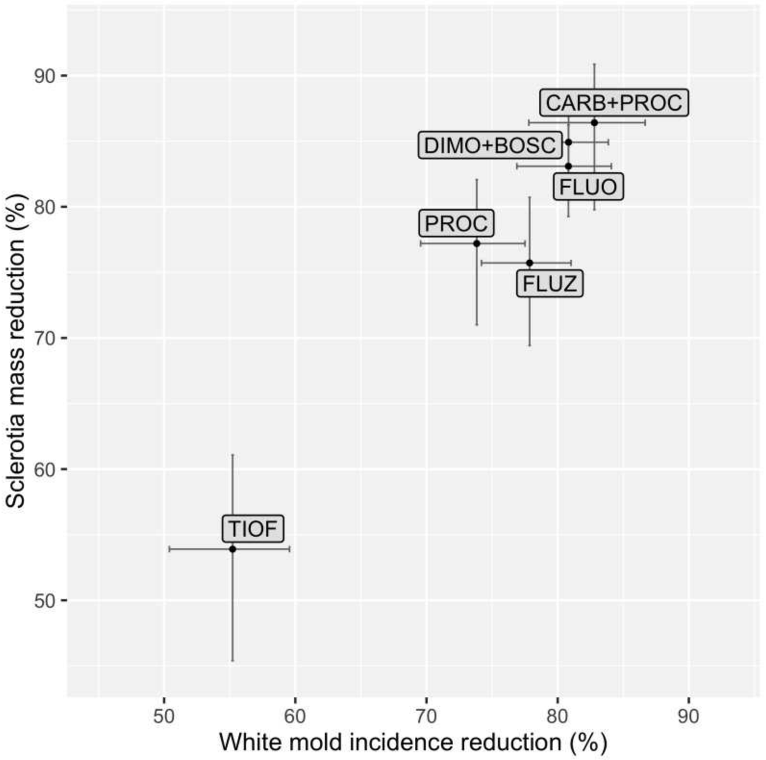


Figure 5: Relationship between percent reduction of white mold incidence (%) and percent reduction of sclerotia mass reduction (%) for five fungicides applied applied twice (flowering and 10 days later) and one applied four times (TIOF) evaluated in a network meta-analysis of 76 trials from 2008/9 to 2016/17 in Brazil. Vertical and horizontal error bars represent the upper and lower limits of 95% confidence intervals around mean estimates for both response variables.

Yield in the check and fungicide-treated plots

Baseline yield ranged from 1,438 to 4,526 kg/ha (median = 2,856 kg/ha) across the trials. As expected, yield levels were higher in the fungicide-treated plots than in the non-treated check. Similar to epidemic levels, there was a high variation in yield among the seasons and within (locations) a season. The highest median yield (3,860.5 kg/ha) was observed in the 2014/15 season and the lowest (2,265.0 kg/ha) during the 2008/09 crop season (Figure 6).

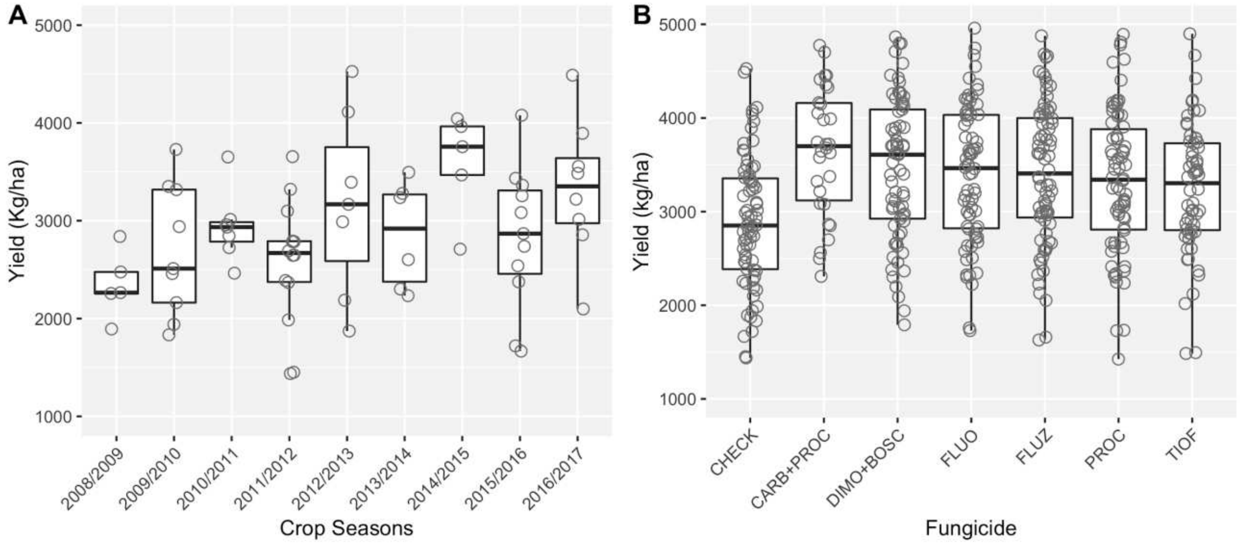


Figure 6: Box plots for the means of grain yield (kg/ha) in the non-treated check (CHECK) plots of trials conducted during nine years (**A**) and means for a set of fungicide treatments evaluated in 72 trials **(B)**. Fungicides evaluated were applied twice at flowering and 10 days later: dimoxystrobin+boscalid (DIMO+BOSC), fluazinam (FLUZ), fluopyram (FLUO), procymidone (PROC) and carbendazim + procymidone (CARB+PROC). Thiophanate-methyl (TIOF) was applied four times.

Meta-analysis of yield gain

The mean yield gains (differences, $\overline{D}$ from using fungicides (relative to non-treated plots) estimated by the meta-analytic model ranged from 312 to 593 kg/ha among them. Yield gains as high as 550 kg/ha were estimated for three fungicides: FLUZ, DIMO+BOSC and FLUO, not differing among them (*P* > 0.1). These were followed by CARB+PROC (500 kg/ha) and PROC (487 kg/ha) and TIOF (312 kg/ha). The latter differed significantly from all other fungicides (*P* < 0.0001). The difference between the estimated means for the most and least effective fungicide was 281 kg/ha (Table 3). Wald test for the treatment x design interaction showed that the network was consistent (*P* = 0.99).

Table 3: Overall means and respective confidence intervals of the difference ($\bar{D}$[kg/ha]) in yield between fungicide-treated and non-treated soybean plots in a nine-year dataset (2008/9 to 2016/17) of 72 fungicide field trials estimated by an arm-based meta-analytic model.

Fungicide[a]	**k**[b]	$\bar{D}$	**CI$_L$**[c]	**CI$_U$**[c]
DIMO+BOSC	70	587.9	483.4	692.3
FLUZ	71	593.8	484.6	702.9
CARB+PROC	30	516.1	410.8	621.3
FLUO	71	551.3	463.5	639.1
PROC	69	487.1	402.8	571.3
TIOF	60	312.0	229.7	394.3

[a] The five selected fungicides were applied twice (flowering and 10 days later), but one was applied four times (flowering and 10-day intervals). See Table 1 for complete information of the evaluated fungicides; [b] number of trials that each fungicide was evaluated; [c] upper (**CI$_U$**) and lower (**CI$_L$**) limits of the 95% confidence interval around $\bar{C}_{INC}$ and $\bar{C}_{SCL}$.

Relationship between control efficacy and yield gain

In general, the pattern of the relationship between each disease reduction (incidence or sclerotia) and yield gains from using fungicides was very consistent. The fungicide treatment leading to the highest mean disease control, CARB+PROC, was behind other three fungicides with regards yield gain and closer to PROC alone, with around 10 percentage points lower than CARB+PROC in disease control. TIOF consistently provided the least gain in yield and reduction of white mold incidence (Figure 7).

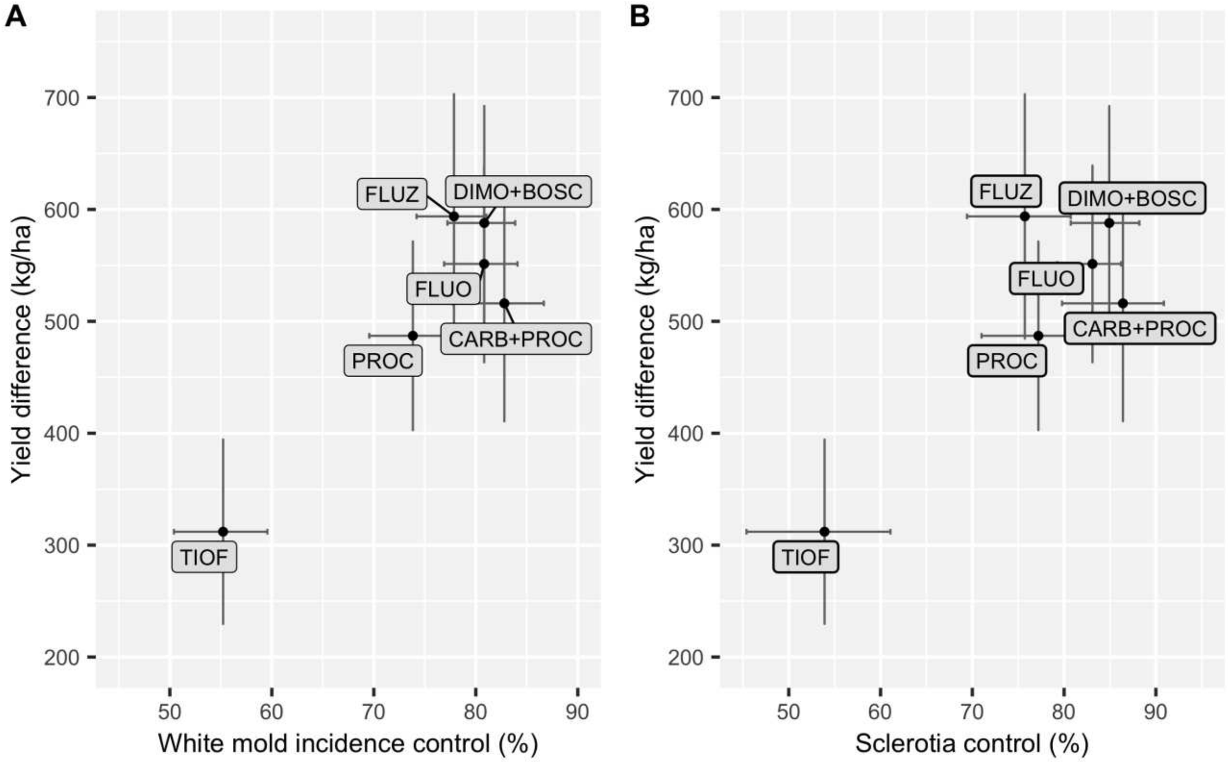


Figure 7: Relationship between percent reduction of white mold incidence (A) or sclerotia amount (B) and yield increase relative to non-treated plots, for five fungicides applied twice (flowering and 10 days later) and one applied four times (TIOF). Data were obtained from a cooperative network of 72 independent fungicide trials in Brazil from 2008/9 to 2016/17. Bars show the upper and lower limits of 95% confidence intervals around black point estimates for both responses.

Effect of baseline disease on yield gain

The expanded model including an interaction term (baseline incidence) differed significantly from the simpler model based on the likelihood ratio test (LRT) test (*P* = 0.03), meaning that incidence in the check explained (5% significance) portion of the variability in yield response. We found that yield response was consistently higher in trials where disease incidence was higher than 30% (Table 4). The differences between the two incidence classes ranged from 183 kg/ha (TIOF) to as high as 312 kg/ha (DIMO+BOSC) among the fungicide treatments.

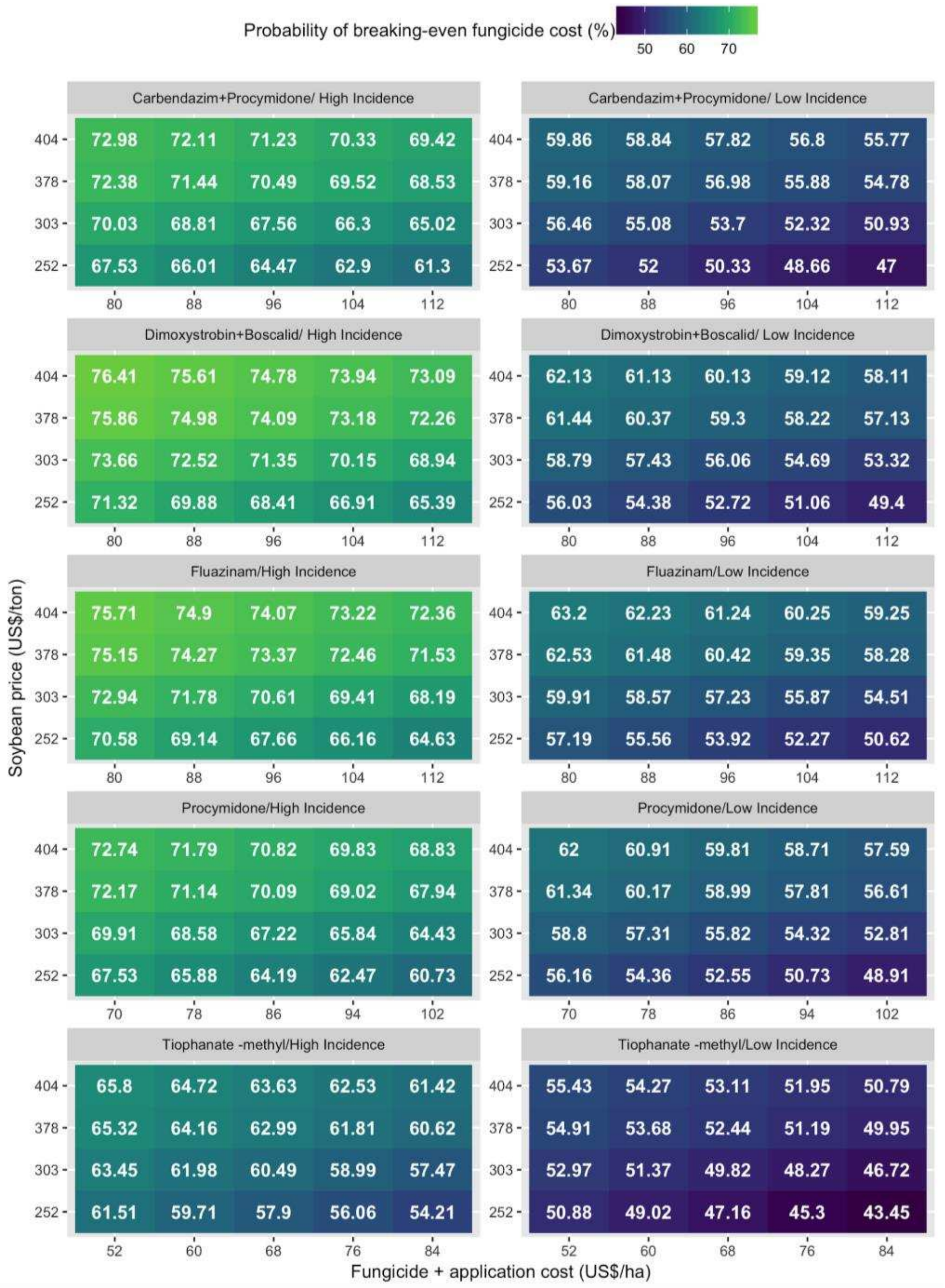
Table 4: Meta-analytic estimates of mean yield difference ($\overline{D}$) between fungicide-treated and non-treated plots for each class of incidence representing a low or high (> 30% disease incidence in the non-treated check) in 72 field trials conducted in Brazil from 2008/9 to 2016/17.

Fungicide[a]	**Disease***	$\overline{D}$	**CI$_L$**[c]	**CI$_U$**[c]	***P-value***	***tau*** ($\hat{\tau}$)[b]
DIMO+BOSC	High	745.70	606.07	885.32	0.0019	578,849.15
	Low	433.04	25.13	749.66		
CARB+PROC	High	662.36	507.07	817.64	0.0092	574,989.83
	Low	387.40	96.14	769.94		
FLUO	High	688.19	571.81	804.57	0.0013	550,165.56
	Low	417.14	136.12	698.16		
FLUZ	High	732.13	583.12	881.14	0.0098	586,834.06
	Low	456.47	98.23	814.70		
PROC	High	594.17	479.36	708.97	0.0129	483,843.22
	Low	385.77	106.67	664.86		
TIOF	High	405.23	292.38	518.07	0.0234	461,275.99
	Low	221.48	-50.25	493.20		

[a] See Table 1 for complete information of the evaluated fungicides; [b] Between-study variance; [c] upper (**CI$_U$**) and lower (**CI$_L$**) limits of the 95% confidence interval; *Disease class defined using a 30% threshold for white mold incidence.

Probability of breaking-even on fungicide cost

The estimates of $\overline{D}$ and between-study variance ($\hat{\tau}$) for each baseline disease (Table 4) were then used to calculate the probability of breaking even on fungicide costs. As expected, lower probability values in general were calculated for the low-disease than high-disease scenarios, and for fungicides that were least effective to protect yields (Figure 8). For instance, four applications of TIOF was more likely to be profitable (> 55% probability) for the high-disease scenario only. The same was found for the other four fungicides where probabilities ranged from 60 to 75% of breaking even on costs for the high-disease scenario. For the low-disease scenario, higher chances of profitability (> 60%) from using the more effective/expensive fungicides were calculated for scenarios of high benefit/cost ratios, as depicted in Figure 9 using the same range of soybean prices and application costs.



Carbendazim+Procymidone/ High Incidence

	80	88	96	104	112
404	72.98	72.11	71.23	70.33	69.42
378	72.38	71.44	70.49	69.52	68.53
303	70.03	68.81	67.56	66.3	65.02
252	67.53	66.01	64.47	62.9	61.3

Carbendazim+Procymidone/ Low Incidence

	80	88	96	104	112
404	59.86	58.84	57.82	56.8	55.77
378	59.16	58.07	56.98	55.88	54.78
303	56.46	55.08	53.7	52.32	50.93
252	53.67	52	50.33	48.66	47

Dimoxystrobin+Boscalid/ High Incidence

	80	88	96	104	112
404	76.41	75.61	74.78	73.94	73.09
378	75.86	74.98	74.09	73.18	72.26
303	73.66	72.52	71.35	70.15	68.94
252	71.32	69.88	68.41	66.91	65.39

Dimoxystrobin+Boscalid/ Low Incidence

	80	88	96	104	112
404	62.13	61.13	60.13	59.12	58.11
378	61.44	60.37	59.3	58.22	57.13
303	58.79	57.43	56.06	54.69	53.32
252	56.03	54.38	52.72	51.06	49.4

Fluazinam/High Incidence

	80	88	96	104	112
404	75.71	74.9	74.07	73.22	72.36
378	75.15	74.27	73.37	72.46	71.53
303	72.94	71.78	70.61	69.41	68.19
252	70.58	69.14	67.66	66.16	64.63

Fluazinam/Low Incidence

	80	88	96	104	112
404	63.2	62.23	61.24	60.25	59.25
378	62.53	61.48	60.42	59.35	58.28
303	59.91	58.57	57.23	55.87	54.51
252	57.19	55.56	53.92	52.27	50.62

Procymidone/High Incidence

	70	78	86	94	102
404	72.74	71.79	70.82	69.83	68.83
378	72.17	71.14	70.09	69.02	67.94
303	69.91	68.58	67.22	65.84	64.43
252	67.53	65.88	64.19	62.47	60.73

Procymidone/Low Incidence

	70	78	86	94	102
404	62	60.91	59.81	58.71	57.59
378	61.34	60.17	58.99	57.81	56.61
303	58.8	57.31	55.82	54.32	52.81
252	56.16	54.36	52.55	50.73	48.91

Tiophanate -methyl/High Incidence

	52	60	68	76	84
404	65.8	64.72	63.63	62.53	61.42
378	65.32	64.16	62.99	61.81	60.62
303	63.45	61.98	60.49	58.99	57.47
252	61.51	59.71	57.9	56.06	54.21

Tiophanate -methyl/Low Incidence

	52	60	68	76	84
404	55.43	54.27	53.11	51.95	50.79
378	54.91	53.68	52.44	51.19	49.95
303	52.97	51.37	49.82	48.27	46.72
252	50.88	49.02	47.16	45.3	43.45

Figure 8: Heat maps for probability of breaking even on fungicide investment for different scenarios of soybean prices and fungicide costs (product+application [10.00 U$/ha]) for five fungicides applied twice (flowering and 10 days later), and one (thiophanate-methyl) applied four times (flowering and 10-day intervals) for white mold control. Different estimates of $\overline{D}$, and respective between-study variance ($\hat{\tau}$), for each disease class representing a low or high-disease scenario (Table 5), obtained from meta-analysis of data from 72 trials conducted over nine growing seasons, were used to calculate the specific probabilities.

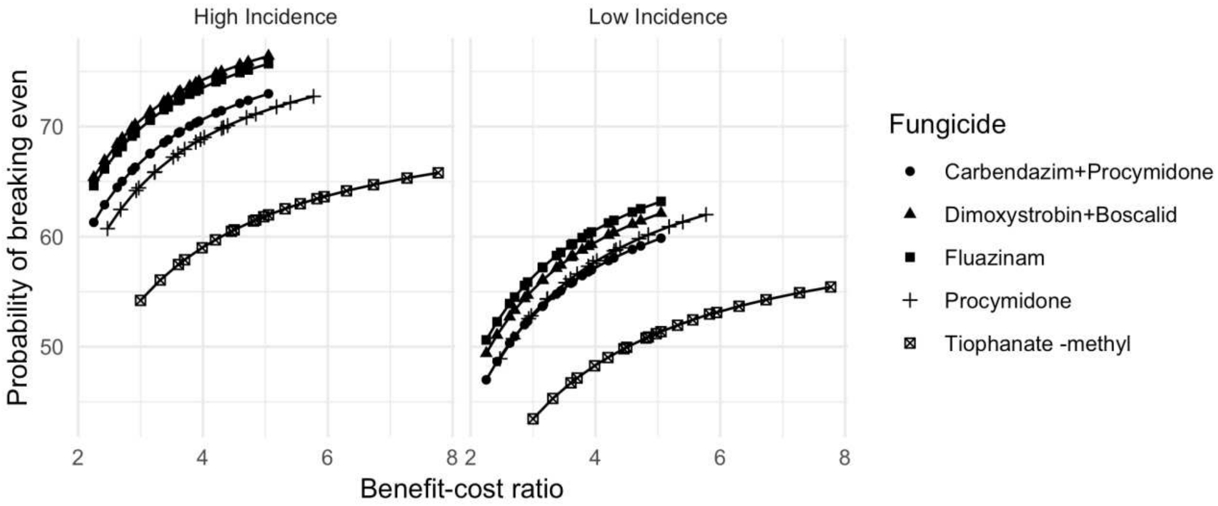


Figure 9: Probability of breaking-even on costs of two sprays of fungicides (except Thiophanate-methyl applied four times) for white mold control in soybean for a range of benefit-cost ratio calculated using a range of expected benefit (soybean prices from 252 to 404 U$/ha) and costs (including operational costs [fixated at 10 U$/ha] from 52 to 84 U$/ha).

DISCUSSION

In this study, we used a network meta-analytic approach to compare the performance of six fungicide formulations commonly evaluated together during nine years of experimentation across a range of environments in Brazil. Previously, meta-analysis was used to summarize the effect of only one fungicide (fluazinam) on white mold control (incidence and severity) and soybean yield. That study used data from 18 trials conducted during six growing seasons in the south of Paraná State (Tupich et al. 2017). We further used the mean and uncertainty of the meta-analytic estimates in risk analysis for aiding decision making with regards the profitability of each of the registered fungicides under a range of scenarios.

As in previous studies in the field, the NMA models allowed us to compare fungicides and provide quantitative estimates of effect sizes and their uncertainty using all available evidence in a unified modeling framework (Paul et al. 2008; Machado et al. 2017). The statistical analyses of the raw data, published in the annual reports, have been limited to comparing treatment means (multiple comparison tests) within a same trial or a same growing season, thus failing to properly provide quantitative estimates of yield benefits (yield gain or difference), a variable that is more relevant for decision-making and economic analysis. Other advantages of NMA include higher statistical power, weighting of the estimates, and treating studies as random effects, thus allowing to make inferences to the population (Madden et al. 2016).

Beside estimating an overall mean effect-size, expansion of the meta-analytic model allows to to explain, at least a portion of heterogeneity of the estimate through moderator analysis. In our study, the significant heterogeneity in yield gain was explained by the baseline disease, here representing trial-specific agronomic, inoculum and weather-related factors. In fact, this was expected given the strong association between white mold and soybean yield (Lehner et al. 2016) and the more limited value of fungicides when baseline disease is relatively low or nearly absent (Paul et al. 2011; Edwards-Molina et al. 2018). A three-location study conducted in central Paraná, Brazil, did not report significant effect (using a non-parametric test) on soybean yield for most of the 17 treatments (combinations of fungicides and number of applications) evaluated for the control of white mold in soybean (Wutzki et al. 2016). The incidence levels in those trials were below 32%, thus suggesting the limited value of fungicides when conditions are not very favorable for epidemics. Interestingly, in most cases, the fungicides evaluated in that study effectively reduced disease incidence and sclerotia mass compared to the control, but failed to reduce disease severity. The appraisal of the means depicted in the bar graphs for each of the three trials of the Wutzki et al. (2016) study, suggests a numerical increase in yield relative to the control treatment, for several fungicides, at levels that fall within our estimated yield gain for the low-disease scenario. The failure to detect such differences may be due to the low power of single experiments (only four replicates) and the focus on the means rather than effect-sizes, as in meta-analysis.

We found that three fungicides, FLUZ, DIMO+BOSC and FLUO, performed best and similarly with regards maximizing yield: mean estimates of yield increase ranged from 688 to 745 kg/ha for the high-disease scenario. Intriguingly, CARB+PROC was ranked first with regards to disease control (both incidence and scleroria mass) but the estimated mean yield gain was significantly lower than those three fungicides. Conversely, FLUZ although not leading to highest control efficacy, ranked best with regards to yield gain.

In the previous meta-analysis of fluazinam effect on soybean yield, data from 18 experiments conducted in the central (Campos Gerais) region of PR state, Brazil, were used and an overall gain of 413.9 kg/ha (IC95% 344.6 to 483.1) was estimated using a random-effects model (Tupich et al. 2017). This value is lower than our overall estimate (486 to 702 kg/ha) for FLUZ applied twice. Similar to our study, the authors tested the effect of two disease levels as moderator of the yield gains (15% threshold for severity and 35% threshold for incidence). However, contrary to our findings, the moderator did not affect yield gain. In that work, the number of entries (21 and 24) was much lower than in our study (77 entries) and used treatments with one, two or three applications of FLUZ, which may explain the different findings.

Comparable levels of control efficacy levels (incidence and severity) of FLUZ and PROC applied twice during flowering were reported in a two-year study conducted in Paraná state, Brazil. However, PROC led to higher reduction of sclerotia mass than FLUZ, which is in agreement with our results (Berger Neto et al. 2017). The authors discussed that the difference may be due to the systemicity of PROC that extends the effect of the fungicide, preventing mycelium formation.

We found that TIOF was least effective for white mold control. In the midwestern United States, Muller et al. (2002) reported 63% efficacy of TIOF applied twice during soybean flowering, which is above our estimated confidence interval for this benzimidazole fungicide. Such difference may be partially explained by location-specific factors and different doses, 0.84 to 1.12 kg/a.i./ha, which were higher than the doses applied in the Brazilian trials (0.5 kg/a.i./ha). Although less effective to protect yield, our risk analysis showed that the yield response from applying four sprays of TIOF may likely break even the costs under more favorable conditions for epidemics, given its lower cost compared to the most effective, but more expensive. However, higher probabilities were estimated for FLUZ and other most effective fungicides, which are less prone to fungicide resistance compared to TIOF (Koenraadt et al. 1992; Lehner et al. 2015). Studies on fungicide resistance in Brazilian *S. sclerotiorum* populations are scarce and a recent work has shown the presence of a TIOF-resistant strain from a common bean production region where the fungicide is regularly used (Lehner et al. 2015). Further studies are needed to check whether TIOF-resistant populations are present in soybean regions where application of TIOF targeting white mold is frequent. Given the availability of more profitable fungicides and the risk of resistance, the use of TIOF should not be encouraged. In fact, our study suggests that application of two sequential sprays of any of the fungicides may not be profitable under low-disease risk scenario, which was also the most uncertain estimate (wide confidence intervals). However, under high disease pressure, considering the similar cost of the most effective fungicides, there is more than one option and the decision of which fungicide to apply shall take other factors into account including logistics and availability.

The information provided in our study may be of greater value should it be incorporated into a decision support system that takes not only economic scenarios (soybean price and application costs) but also disease risk into account, using white mold forecasting models (Willbur et al. 2018). We are not aware of warning systems being used for predicting white mold on Brazilian soybean. The current database of the cooperative trials provide a rich source for validating existing models or developing new ones specific to Brazilian conditions.

REFERENCES

Abawi, G. S., and Grogan, R. G. 1979. Epidemiology of diseases caused by *Sclerotinia* species. Phytopathology. 69: 899–904.

Adams, P., and Ayers, W. A. 1979. Ecology of *Sclerotinia* species. Phytopathology. 69:896–898.

Avenot, H. F., and Michailides, T. J. 2010. Progress in understanding molecular mechanisms and evolution of resistance to succinate dehydrogenase inhibiting (SDHI) fungicides in phytopathogenic fungi. Crop Prot. 29:643–651.

Belova, A., Narayan, T., and Olkin, I. 2013. Methyl bromide alternatives for strawberry and tomato pre-plant uses: A meta-analysis. Crop Prot. 54:1–14.

Boland, G. J., and Hall, R. 1994. Index of plant hosts of *Sclerotinia sclerotiorum*. Canadian Journal of Plant Pathology. 16:93–108.

Bosch, F. van den, Oliver, R., Berg, F. van den, and Paveley, N. 2014. Governing Principles Can Guide Fungicide-Resistance Management Tactics. Annu. Rev. Phytopathol. 52:175–195.

Brent, K. J., and Hollomon, D. W. 2007. Fungicide resistance in crop pathogens: how can it be managed? FRAC Monograph No. 1 (second, revised edition). Fungicide Resistance Action Committee.

Clarkson, J. P., Fawcett, L., Anthony, S. G., and Young, C. 2014. A model for *Sclerotinia sclerotiorum* infection and disease development in lettuce, based on the effects of temperature, relative humidity and ascospore density. PLoS One. 9:15–25.

Edwards-Molina, J. P., Paul, P. A., Amorim, L., da Silva, L. H. C. P., Siqueri, F. V., Borges, E. P., Campos, H. D., Nunes Junior, J., Meyer, M. C., Martins, M. C. 2018. Meta-analysis of fungicides efficacy on soybean target spot and cost-benefit assessment. Plant Pathology; doi:10.1111/ppa.12925.

Elderfield, J. A. D., Lopez-Ruiz, F. J., Bosch, van den F., and Cunniffe, N. J. 2018. Using epidemiological principles to explain fungicide resistance management strategies: why do mixtures outperform alternations? Phytopathology. 44:1–69.

Fall, M. L., Boyse, J. F., Wang, D., Willbur, J. F., Smith, D. L., and Chilvers, M. I. 2018. Case Study of an Epidemiological Approach Dissecting Historical Soybean Sclerotinia Stem Rot Observations and Identifying Environmental Predictors of Epidemics and Yield Loss. Phytopathology. 108: 469-478.

Hou, Y. P., Mao, X. W., Lin, S. P., Song, X. S., Duan, Y. B., and Wang, J. X. 2018. Activity of a novel succinate dehydrogenase inhibitor fungicide pyraziflumid against *Sclerotinia sclerotiorum*. Pestic. Biochem. Physiol. 145:22–28.

Huang, C., Sun, Z., Wang, H., Luo, Y., and Ma, Z. 2012. Effects of wheat cultivar mixtures on stripe rust: A meta-analysis on field trials. Crop Prot. 33:52–58.

Lehner, M. S., Del Ponte, E. M., Gugino, B. K., Kikkert, J. R., and Pethybridge, S. J. 2017. Sensitivity and Efficacy of Boscalid, Fluazinam, and Thiophanate-Methyl for White Mold Control in Snap Bean in New York. Plant Dis. 101:1253–1258.

Lehner, M. S., Pethybridge, S. J., Meyer, M. C., and Del Ponte, E. M. 2017. Meta-analytic modelling of the incidence–yield and incidence–sclerotial production relationships in soybean white mould epidemics. Plant Pathol. 66:460–468.

Liang, H. J., Di, Y. L., Li, J. L., and Zhu, F. X. 2015. Baseline sensitivity and control efficacy of fluazinam against *Sclerotinia sclerotiorum*. Eur. J. Plant Pathol. 142:691–699.

Liu, Y., Liu, H., Li, X., Han, J., and Liu, H. 2010. Biological, physiological and biochemical characteristics of procymidone-resistant *Sclerotinia sclerotiorum*. Chin. Agric. Sci. Bull. 26: 277 - 281.

Lu, G., and Ades, A. 2009. Modeling between-trial variance structure in mixed treatment comparisons. Biostatistics. 10:792–805.

Lu, G., and Ades, A. E. 2004. Combination of direct and indirect evidence in mixed treatment comparisons. Stat. Med. 23:3105–3124.

Lumley, T. 2002. Network meta-analysis for indirect treatment comparisons. Stat. Med. 21:2313–2324.

Ma, Z., and Michailides, T. J. 2005. Advances in understanding molecular mechanisms of fungicide resistance and molecular detection of resistant genotypes in phytopathogenic fungi. Crop Prot. 24:853–863.

Machado, F. J., Santana, F. M., Lau, D., and 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 Dis. 101: 1633 - 1641.

Madden, L. V., Piepho, H.-P., and Paul, P. A. 2016. Statistical models and methods for network meta-analysis. Phytopathology. 106:792–806.

Mahoney, K. J., McCreary, C. M., and Gillard, C. L. 2014. Response of dry bean white mould [*Sclerotinia sclerotiorum* (Lib.) de Bary, causal organism] to fungicides. Can. J. Plant Sci. 94:905–910.

McCreary, C. M., Depuydt, D., Vyn, R. J., and Gillard, C. L. 2016. Fungicide efficacy of dry bean white mold [*Sclerotinia sclerotiorum* (Lib.) de Bary, causal organism] and economic analysis at moderate to high disease pressure. Crop Prot. 82:75–81.

McDonald, M. R., Kooi, K. D. V, and Westerveld, S. M. 2008. Effect of foliar trimming and Fungicides on apothecial number of *Sclerotinia sclerotiorum*, leaf blight severity, yield, and canopy microclimate in carrot. Plant Dis. 92:132–136.

Meyer, M. C., Campos, H. D., Godoy, C. V., and Utiamada, C. M. 2016. Ensaios cooperativos de controle biológico de mofo-branco na cultura da soja -safras 2012 a 2015. Documento 368. Londrina, Brazil: Empresa Brasileira de Pesquisa Agropecuária.

Meyer, M. C., Campos, H. D., Godoy, C. V., Utiamada, C. M., 2014. Ensaios cooperativos de controle químico de mofo branco na cultura da soja: safras 2009 a 2012. Documentos 345. Londrina, Brazil: Empresa Brasileira de Pesquisa Agropecuária.

Meyer, M. C., Campos, H. D., Godoy, C. V., Utiamada, C. M., Pimenta, C. B., and Jaccoud Filho, D. S. 2015. Eficiência de fungicidas para controle de mofo-branco (*Sclerotinia sclerotiorum)* em soja, na safra 2014/2015: resultados sumarizados dos ensaios cooperativos. Circular Técnica 114. Londrina, Brazil: Empresa Brasileira de Pesquisa Agropecuária.

Meyer, M. C., Campos, H. D., Godoy, C. V., Utiamada, C. M., Pimenta, C. B., and Jaccoud Filho, D. S. 2017. Eficiência de fungicidas para controle de mofo-branco (*Sclerotinia sclerotiorum)* em soja, na safra 2016/17: resultados sumarizados dos ensaios cooperativos. Circular Técnica 133. Londrina, Brazil: Empresa Brasileira de Pesquisa Agropecuária.

Meyer, M. C., Campos, H. D., Godoy, C. V., Utiamada, C. M., Pimenta, C. B., and Machado, A. Q. 2015. Eficiência de fungicidas para controle de mofo-branco (*Sclerotinia sclerotiorum)* em soja, na safra 2013/2014: resultados sumarizados dos ensaios cooperativos. Circular Técnica 109. Londrina, Brazil: Empresa Brasileira de Pesquisa Agropecuária.

Meyer, M. C., Campos, H. D., Godoy, C. V., Utiamada, C. M., Pimenta, C. B., Jaccoud Filho, D. S., and Borges, E. P. 2016. Eficiência de fungicidas para controle de mofo-branco (*Sclerotinia sclerotiorum*) em soja, na safra 2015/2016: resultados sumarizados dos ensaios cooperativos. Circular Técnica 122. Londrina, Brazil: Empresa Brasileira de Pesquisa Agropecuária.

Miorini, T. J. J., Raetano, C. G., and Everhart, S. E. 2017. Control of white mold of dry bean and residual activity of fungicides applied by chemigation. Crop Prot. 94:192–202.

New Use Review, Fluazinam. 2012. Minnesota Department of Agriculture. 1–2.

Ngugi, H. K., Lehman, B. L., and Madden, L. V. 2011. Multiple treatment meta-analysis of products evaluated for control of fire blight in the eastern United States. Phytopathology. 101:512–22.

Ojiambo, P. S., Paul, P. A., and Holmes, G. J. 2010. A Quantitative Review of Fungicide Efficacy for Managing Downy Mildew in Cucurbits. Phytopathology. 100:1066–1076.

Paul, P. A., Madden, L. V., Bradley, C. A., Robertson, A. E., Munkvold, G. P., and Shaner, G. 2011. Meta-analysis of yield response of hybrid field corn to foliar fungicides in the U.S. Corn belt. Phytopathology. 101:1122–1132.

Peltier, A. J., Bradley, C. A., Chilvers, M. I., Malvick, D. K., Mueller, D. S., and Wise, K. A. 2012. Biology, Yield loss and Control of Sclerotinia Stem Rot of Soybean. J. Integr. Pest Manag. 3:1–7.

Salam, K. P., Thomas, G. J., Beard, C., Loughman, R., MacLeod, W. J., and Salam, M. U. 2013. Application of meta-analysis in plant pathology: A case study examining the impact of fungicides on wheat yield loss from the yellow spot-septoria nodorum blotch disease complex in Western Australia. Food Secur. 5:319–325.

Salanti, G., Higgins, J. P. T., Ades, A. E., and Ioannidis, J. P. A. 2008. Evaluation of networks of randomized trials. Stat. Methods Med. Res. 17:279–301.

Schwartz, H. F., and Steadman, J. R. 1978. Factors affecting sclerotium populations of, and apothecium production by, *Sclerotinia sclerotiorum*. Phytopathology. 68:383.

Sumida, C. H., Canteri, M. G., Peitl, D. C., Tibolla, F., Orsini, I. P., and Araújo, F. A. 2015. Chemical and biological control of Sclerotinia stem rot in the soybean crop. Ciência Rural. :760–766.

Teixeira, I. R., Carvalho, L. R. de, Reis, E. F. dos, Silva, A. G. da, and Teixeira, G. C. da S. 2013. The Effectiveness of Interaction Between Chemical Fungicides, Bio-Agent and Plant Densities on the White Mold Disease in the Common Bean. J. Agric. Sci. 5:255–261.

Tupich, F. L. B., Fantin, L. H., Silva, A. L. da, and Canteri, M. G. 2017. Impacto do controle do mofo-branco com fluazinam na produtividade da soja no Sul do Paraná: metanálise. Summa Phytopathol. 43:145–150.

Vieira, R. F., Paula Júnior, T. J., Teixeira, H., and de S. Carneiro, J. E. 2010. White Mold Management in Common Bean by Increasing Within-Row Distance Between Plants. Plant Dis. 94:361–367.

Willbur, J.F., Fall, M.L., Bloomingdale, C., Byrne, A.M., Chapman, S.A., Isard, S.A., Magarey, R.D., McCaghey, M., Mueller, B.D., Russo, J.M., Schlegel, J., Chilvers, M.I., Mueller, D.S., Kabbage, M., and Smith, D.L. 2018. Weather-based models for assessing the risk of *Sclerotinia sclerotiorum* apothecial presence in soybean (*Glycine max*) fields. Plant Dis. 102:73-84.

Willyerd, K. T., Li, C., Madden, L. V., Bradley, C. A., Bergstrom, G. C., and Sweets, L. E. 2012. Efficacy and Stability of Integrating Fungicide and Cultivar Resistance to Manage Fusarium Head Blight and Deoxynivalenol in Wheat. Plant Dis. 96:957–967.

Wutzki, C. R., Jaccoud Filho, D. S., Berger Neto, A., Tullio, H. E., Juliatti, F. C., and Nascimento, A. J. 2016. Redução do nível de mofo-branco na soja pelo manejo de fungicidas. Biosci. J. 32:642–651.

Young, C. S., Clarkson, J. P., Smith, J. A., Watling, M., Phelps, K., and Whipps, J. M. 2004. Environmental conditions influencing *Sclerotinia sclerotiorum* infection and disease development in lettuce. Plant Pathol. 53:387–397.

Zhang, J., Carlin, B. P., Neaton, J. D., Soon, G. G., Nie, L., Kane, and R. 2014. Network meta-analysis of randomized clinical trials: Reporting the proper summaries. Clin. Trials. 11:246–262.

Zhou, F., Zhang, X. L. , Li, J. L., and Zhu, F. X. 2014. Dimethachlon resistance in *Sclerotinia sclerotiorum* in China. Plant Disease. 98: 1221 - 1226.

APPENDIX

Table S1: Summary information for 72 trials where it was tested the effect of dimoxystrobin+boscalid (DIMO+BOSC), fluazinam (FLUZ), fluopyram (FLUO), procymidone (PROC), thiophanate-methyl (TIOF) and carbendazim + procymidone (CARB+PROC) applied twice (flowering and 10 days later) and thiophanate-methyl (TIOF) applied four times (flowering and 10-day intervals) on white mold control in Brazil from 2008/9 to 2016/17.

Trial	Season	Location	Long	Lat	State	Elevation	Region	Cultivar
1	2008/09	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	P98Y11
2	2008/09	São Miguel do Passa Quatro	48°45'13"	16°51'46"	GO	1031	Northern	M 7908 RR
3	2008/09	Silvânia	47°46'08"	14°57'54"	GO	1050	Northern	CD 219 RR
4	2008/09	Mauá da Serra	51°13’07”	23°53’57”	PR	1029	Southern	BRS 282
5	2008/09	Nova Ponte	47°42'42"	19°24'24"	MG	999	Northern	AN-8500
6	2009/10	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	P98Y11
7	2009/10	São Miguel do Passa Quatro	48°45'13"	16°51'46"	GO	1027	Northern	M 7908 RR
8	2009/10	Água Fria	47°46'08"	14°57'54"	GO	891	Northern	M 7908 RR
9	2009/10	Campo Verde	54°56'17"	15°06'55"	MT	985	Northern	M 8230 RR
10	2009/10	Nova Ponte	47°42'42"	19°24'24"	MG	1005	Northern	M 8200
11	2009/10	Uberlândia	47°56'58"	19°12'54"	MG	947	Northern	BRS Valiosa RR
12	2009/10	Pilar do Sul	47°42'59"	23°48'47"	SP	800	Southern	BRS 231
13	2009/10	Mauá da Serra	51°13’07”	23°53’57”	PR	909	Southern	BRS 232

14	2010/11	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	P98Y11
15	2010/11	São Miguel do Passa Quatro	48°45'13"	16°51'46"	GO	1027	Northern	M 7908 RR
16	2010/11	Silvânia	47°46'08"	14°57'54"	GO	1050	Northern	BRS 8160 RR
17	2010/11	Água Fria	47°46'08"	14°57'54"	GO	891	Northern	M 7639 RR
18	2010/11	Ponta Grossa	50°03'09"	25°05'42"	PR	1021	Southern	BMX Ativa RR
19	2010/11	Mauá da Serra	51°13’07”	23°53’57”	PR	970	Southern	-
20	2010/11	Marilândia do Sul	51°15’30”	23°44’51”	PR	868	Southern	BMX Potência RR
21	2011/12	São Miguel do Passa Quatro	48°45'13"	16°51'46"	GO	1027	Northern	M 7908 RR
22	2011/12	Goianira	49°24'2,7"	16°26'6,3"	GO	737	Northern	M 7908 RR
23	2011/12	Uberlândia	47°56'58"	19°12'54"	MG	947	Northern	P98Y11
24	2011/12	Chapadão do Sul	52°38'38”	18°46'47”	MS	813	Northern	ST 810 RR
25	2011/12	Ponta Grossa	50°03'09"	25°05'42"	PR	1021	Southern	BMX Turbo RR
26	2011/12	Palmeira	50°03'19"	25°25'45"	PR	820	Southern	BMX Apolo RR
27	2011/12	Palmeira	50°03'19"	25°25'45"	PR	820	Southern	BMX Potencia rr
28	2011/12	Planaltina	47°20’06”	15°40’00”	DF	600	Northern	M7908
29	2011/12	São Desiderio	45°57'03"	13°05'33"	BA	844	Northern	M9144
30	2011/12	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	P 98Y11
31	2011/12	Campo Verde	54°56'17"	15°06'55"	MT	736	Northern	TMG 1174 RR

32	2011/12	Campo Verde	54°56'17"	15°06'55"	MT	736	Northern	TMG 1174 RR
33	2011/12	Faxinal	51°15'50"	23°56'53"	PR	998	Southern	BMX TURBO RR
34	2011/12	Capão Bonito	48°22'	24°02'	SP	730	Southern	5909 RR
35	2012/13	Chapadão do Sul	52°38'38”	18°46'47”	MS	813	Northern	P98Y11 RR
36	2012/13	Rio Verde	51°19'30"	17°27'25"	GO	748	Northern	TMG 1179
37	2012/13	Ponta Grossa	50°03'09"	25°05'42"	PR	1021	Southern	BMX Potencia RR
38	2012/13	Jataí	52°07'23"	5°59'16"	GO	749	Northern	Anta 82 RR
39	2012/13	São Miguel do Passa Quatro	48°45'13"	16°51'46"	GO	1027	Northern	Emgopa 313 RR
40	2012/13	Faxinal	51°15'50"	23°56'53"	PR	820	Southern	BRS 284
41	2012/13	Uberlandia	47°56'58"	19°12'54"	MG	947	Northern	P98Y11
42	2012/13	Ponta Grossa	50°03'09"	25°05'42"	PR	1021	Southern	-
43	2013/14	Chapadão do Sul	52°38'38”	18°46'47”	MS	813	Northern	P98Y30 RR
44	2013/14	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	P 98Y11 RR
45	2013/14	Mauá da Serra	51°13’07”	23°53’57”	PR	909	Southern	MONSOY M 5917 IPRO
46	2013/14	Ponta Grossa	50°03'09"	25°05'42"	PR	1021	Southern	FTS Ibyara RR
47	2013/14	São Miguel do Passa Quatro	48°45'13"	16°51'46"	GO	1027	Northern	BMX Desafio RR
48	2013/14	Ponta Grossa	50°03'09"	25°05'42"	PR	1021	Southern	V-top
49	2014/15	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	NA 5909 RR

50	2014/15	Ponta Grossa	50°03'09"	25°05'42"	PR	1021	Southern	NA 5909 RG
51	2014/15	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	Monsoy 8210 IPRO
52	2014/15	Mauá da Serra	51°13’07”	23°53’57”	PR	909	Southern	M Soy 5917
53	2014/15	Silvânia	47°46'08"	14°57'54"	GO	1050	Northern	MSOY 8210 IPRO
54	2015/16	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	MSOY 6972
55	2015/16	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	M 8210 IPRO
56	2015/16	Silvânia	47°46'08"	14°57'54"	GO	1050	Northern	M 8210 IPRO
57	2015/16	Silvânia	47°46'08"	14°57'54"	GO	1050	Northern	M 8210 IPRO
58	2015/16	Uberlândia	47°56'58"	19°12'54"	MG	863	Northern	BG41801RR
59	2015/16	Barreiras	46° 15’ 15”	11° 50’ 12”	BA	454	Northern	M 8349 IPRO
60	2015/16	Júlio de Castilhos	53° 36’ 01”	29° 35’ 13”	RS	513	Southern	NS 5151 IPRO
61	2015/16	Júlio de Castilhos	53° 36’ 01”	29° 35’ 13”	RS	513	Southern	BMX Alvo RR
62	2015/16	Palmeira	50°03'19"	25°25'45"	PR	865	Southern	TMG 7062 IPRO Inox
63	2015/16	Mauá da Serra	51°13’07”	23°53’57”	PR	909	Southern	BMX Garra IPRO
64	2015/16	Faxinal	51°15'50"	23°56'53"	PR	820	Southern	BRS 284
65	2016/17	Ponta Grossa	50°03'09"	25°05'42"	PR	1021	Southern	NA 5909
66	2016/17	Pitanga	51° 46’ 58”	24° 43’ 15”	PR	952	Southern	BMX Ativa RR
67	2016/17	Silvânia	47°46'08"	14°57'54"	GO	1050	Northern	BRS 8170IPRO

68	2016/17	Uberlândia	47°56'58"	19°12'54"	MG	863	Northern	BMX Deafio RR
69	2016/17	Montividiu	51°40’05”	17°25’17”	GO	921	Northern	M8372 Ipro
70	2016/17	Chapadão do Sul	52°38'38”	18°46'47”	MS	813	Northern	5G8015 IPRO
71	2016/17	Palmeira	50°03'19"	25°25'45"	PR	865	Southern	TMG 7062 IPRO
72	2016/17	Mauá da Serra	51°13’07”	23°53’57”	PR	909	Southern	BRS 284

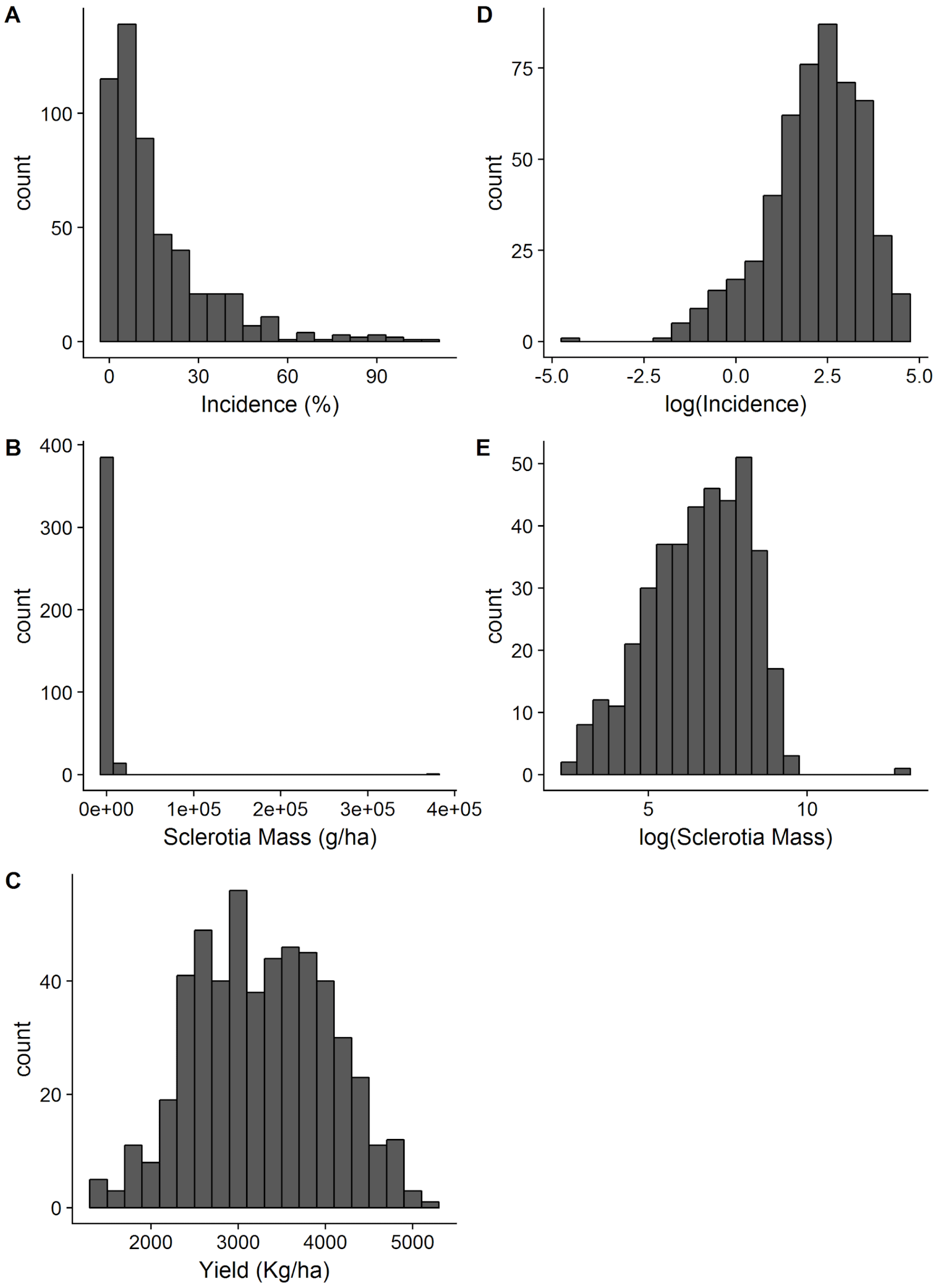


Figure S1: **A** - **C**: Histograms for the distribution of white mold incidence, sclerotia mass and yield to check normality; **D** - **E**: log-transformed incidence and sclerotia mass data for normalizing the distribution and use in the meta-analysis.