

**ANA CAROLYNE COSTA DE CARVALHO**

**MODELING THE SEVERITY-YIELD RELATIONSHIP FOR THE LATE SEASON  
DISEASES IN SOYBEAN**

Thesis submitted to the Plant Pathology  
Graduate Program of the Universidade  
Federal de Viçosa in partial fulfillment of the  
requirements for the degree of *Magister  
Scientiae*.

Adviser: Emerson Medeiros Del Ponte

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## ABSTRACT

CARVALHO, Ana Carolyne Costa de, M.Sc., Universidade Federal de Viçosa, September, 2024. **Modeling the severity-yield relationship for the late season diseases in soybean.** Adviser: Emerson Medeiros Del Ponte.

*Cercospora* leaf blight and purple seed stain caused by *Cercospora* species, and *Septoria* brown spot caused by *Septoria glycines*, are three of the main diseases that make up the late season diseases complex in soybean, reducing grain yield and quality due to symptoms that appear with greater intensity during the reproductive stage of the crop. The datasets of late season diseases severity and yield used in this study ( $n = 39$  trials) were obtained from field trials conducted across nine states in Brazil over four growing seasons (2020–2024) as part of a cooperative network aimed at comparing the efficacy of fungicides in controlling late season diseases. In the present study, Pearson's correlation coefficient ( $r$ ) and Fisher's transformation ( $Z$ ) were calculated to investigate the association between disease severity estimated at the critical point (between phenological stages R6 and R7) and soybean yield. Additionally, a random-effects meta-analysis was conducted to calculate the intercept ( $\beta_0$ ) and slope ( $\beta_1$ ) coefficients of the linear regression model. Disease pressure (low severity =  $\leq 35\%$  and high severity =  $> 35\%$ ), yield class (low =  $\leq 3,745$  kg/ha and high =  $> 3,745$  kg/ha), region (trials conducted below  $20^\circ\text{S}$  were classified as south, and others as north), altitude ( $< 635$  m or  $\geq 635$  m above sea level), and year were included as categorical moderators that could explain at least part of the observed heterogeneity. Based on the  $\beta_0$  and  $\beta_1$  values, the damage coefficient (in percentage) was calculated by dividing the estimated slope by the estimated intercept and multiplying the result by 100. The economic damage threshold was also calculated based on the estimated damage coefficient, various attainable yield and fungicide efficacy values. There was a moderate negative correlation between late season diseases severity and soybean yield ( $Z = -0.55$ ,  $r = -0.50$ ). Furthermore, a significant negative slope obtained through random-effects meta-analytic modeling confirmed the negative linear relationship between late season diseases severity and soybean yield. The population average estimates for  $\beta_0$  and  $\beta_1$  were 4,589.06 kg/ha and -22.58 kg/ha per unit increase in severity, respectively, according to the random-effects model ( $P < 0.001$ ). None of the categorical moderators tested as fixed effects individually affected the slope significantly ( $P > 0.19$ ); however, disease

pressure, yield class, and altitude significantly affected the intercept ( $P < 0.014$ ). Based on the overall intercept and slope averages, the overall relative damage coefficient was estimated at -0.49% (95% CI = -0.61 to -0.38), indicating that a one percent increase in late season diseases severity would result in a 0.49% decrease in soybean yield. For fungicide efficacy ranging from 14% to 88%, the economic damage threshold ranged from 0.41% to 4.33%, with an average of 1.57%, corresponding to an average fungicide efficacy of 54%. In conclusion, we confirmed a significant negative linear relationship between soybean yield and the severity of late season diseases, particularly the complex of *Cercospora* leaf blight, purple seed stain and *Septoria* brown spot, indicating that the findings of this study can enhance integrated disease management programs under different scenarios.

**Keywords:** *Cercospora* spp.; *Septoria glycines*; Damage coefficient; Meta-analysis.

## RESUMO

CARVALHO, Ana Carlyne Costa de, M.Sc., Universidade Federal de Viçosa, setembro de 2024. **Modelagem da relação entre severidade e produtividade para as doenças de final de ciclo em soja.** Orientador: Emerson Medeiros Del Ponte.

O crestamento foliar de *Cercospora* e a mancha-púrpura dos grãos, causadas por espécies de *Cercospora*, e a mancha-parda, causada *Septoria glycines*, são três das principais doenças que compõem o complexo de doenças de final de ciclo na soja, causando redução no rendimento e qualidade dos grãos devido aos sintomas que surgem de forma mais intensa no estágio reprodutivo da cultura. Os conjuntos de dados sobre a severidade das doenças de final de ciclo e o rendimento utilizados neste estudo foram obtidos a partir de ensaios de campo realizados em nove estados do Brasil ao longo de quatro safras de cultivo (2020-2024), como parte de uma rede cooperativa de experimentos destinada a comparar a eficácia dos fungicidas no controle das DFC (n = 39 ensaios). No presente estudo, foram calculados o coeficiente de correlação de Pearson ( $r$ ) e a transformação de Fisher ( $Z$ ) para investigar a associação entre a severidade da doença estimada no ponto crítico (entre os estágios fenológicos R6 e R7) e o rendimento da soja. Além disso, foi realizada uma meta-análise de efeitos aleatórios para calcular os coeficientes de intercepto ( $\beta_0$ ) e inclinação ( $\beta_1$ ) do modelo de regressão linear. Pressão da doença (baixa severidade =  $\leq 35\%$  e alta severidade =  $> 35\%$ ), classe de rendimento (baixa =  $\leq 3.745$  kg/ha e alta =  $> 3.745$  kg/ha), região (ensaios realizados abaixo de  $20^\circ\text{S}$  foram classificados como sul, e os demais como norte), altitude ( $< 635$  m ou  $\geq 635$  m acima do nível do mar) e ano foram incluídos como moderadores categóricos que poderiam explicar ao menos parte da heterogeneidade observada. A partir dos valores de  $\beta_0$  e  $\beta_1$ , foi calculado o coeficiente de dano, dividindo-se a inclinação estimada pelo intercepto estimado e multiplicando o resultado por 100. Também foi calculado o limiar de dano econômico com base no coeficiente de dano estimado, nos diferentes valores de rendimento atingível e na eficácia dos fungicidas. Houve uma correlação negativa moderada entre a severidade das doenças de final de ciclo e o rendimento da soja ( $Z = -0,55$ ,  $r = -0,50$ ). Além disso, uma inclinação negativa significativa obtida através da modelagem meta-analítica de efeitos aleatórios confirmou a relação linear negativa entre a severidade das doenças de final de ciclo e o rendimento da soja. As estimativas para a média populacional do intercepto e da

inclinação foram de 4.589,06 kg/ha e -22,58 kg/ha para cada unidade percentual de severidade, respectivamente, de acordo com o modelo de efeitos aleatórios ( $P < 0,001$ ). Nenhuma das variáveis moderadoras testadas individualmente como efeitos fixos afetou significativamente a inclinação ( $P > 0,19$ ); no entanto, as variáveis moderadoras: pressão da doença, classe de rendimento e altitude afetaram significativamente o intercepto ( $P < 0,014$ ). Com base na média geral do intercepto e da inclinação, o coeficiente de dano relativo geral foi estimado em -0,49% (IC 95% = -0,61 a -0,38), indicando que um aumento percentual na severidade das doenças de final do ciclo resultaria em uma diminuição de 0,49% no rendimento da soja. Para a eficácia dos fungicidas variando de 14% a 88%, o limiar de dano econômico variou entre 0,41% e 4,33%, com uma média de 1,57%, correspondente a uma eficácia média de eficácia de fungicidas de 54%. Em conclusão, confirmamos uma relação linear negativa significativa entre o rendimento da soja e a severidade das doenças de final de ciclo, especificamente, para o complexo formado por crestamento foliar de *Cercospora*, mancha-púrpura dos grãos e mancha-parda, de modo que os resultados deste estudo podem aprimorar programas de manejo integrado de doenças sob diferentes cenários.

**Palavras-chave:** *Cercospora* spp.; *Septoria glycines*; Coeficiente de dano; Meta análise.

## SUMMARY

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## 1 INTRODUCTION

Brazil is currently the largest soybean (*Glycine max* [L.]) producer in the world. Together with the United States and Argentina, the three countries are responsible for 80% of global soybean production (Voorra et al., 2024). The crop is grown all over the country, with significant differences in yield being reported across the production regions (Balbinot Junior et al., 2022). Various factors are responsible for reducing soybean yield, including the occurrence of diseases (Hartman et al., 2015a). Late season diseases in soybeans comprise a group of various diseases that affect different parts of the plant, usually appearing later in the growing season, causing premature senescence and leading to an average yield reduction from 10 to 30% (Carmona et al., 2015, 2017), even though the severity of these diseases in the field is usually not very high (~20%) (Godoy et al., 2021, 2022, 2023, 2024).

*Septoria* brown spot caused by *Septoria glycines* and *Cercospora* leaf blight and purple seed stain caused by *Cercospora* spp., are the most prevalent late season diseases in Brazil (Sautua et al., 2024). Symptoms commonly occur at the end of the soybean cycle, leading to premature defoliation of the crop. However, these pathogens can be present in the field throughout the entire growing season (Seixas et al., 2020; Godoy et al., 2023).

Since soybean cultivars resistant to late season diseases are not currently available (Carmona et al., 2015), management of these diseases relies primarily on chemical control. The application of chlorothalonil and mixtures of demethylation inhibitors (DMI), quinone outside inhibitors (QoI) and succinate dehydrogenase inhibitors (SDHI) between R1 and R6 stages can effectively control late season diseases (Sautua et al., 2024). However, the effectiveness of fungicides has been significantly reduced due to the emergence of *Cercospora* spp. isolates that exhibit resistance or low sensitivity to several commonly used fungicides (Seixas et al., 2020).

Field trials comparing the efficacy of fungicides for controlling late season diseases have been conducted by a research network since the 2020/2021 growing season in various regions of Brazil, covering the country's main soybean-producing areas. These data allow for the study of the relationship between late season diseases severity and soybean yield, similar to previous studies on yield loss modeling for soybean diseases using multiple-trial data (Dalla Lana et al., 2015; Lehner et al., 2017;

Barro et al., 2023; Kandel et al., 2020). This methodology allows, among other objectives, to quantitatively summarize the relationship between disease and yield by integrating the results of multiple studies (Borenstein et al., 2009; Madden et al., 2016).

Therefore, the main objectives of this work were to: i) explore and quantitatively summarize the relationship between soybean yield and the severity of late season diseases from multiple field experiments; and ii) identify possible variables affecting this relationship. In addition, the economic damage threshold was calculated based on the damage coefficient derived from this study, considering scenarios of control efficacy, attainable yield, soybean price and chemical control costs.

## 2 LITERATURE REVIEW

### 2.1 Origin, spread and impact of late season soybean diseases

In soybean, the most common late season diseases include anthracnose (*Colletotrichum* spp.), pod and stem blight (*Diaporthe* spp.), bacterial blight (*Pseudomonas syringae* pv. *glycinea*), bacterial pustule (*Xanthomonas citri* pv. *glycines*), *Cercospora* leaf blight and purple seed stain (*Cercospora* spp.) and *Septoria* brown spot (*Septoria glycines*) (Sautua et al., 2024). Among these, *Cercospora* leaf blight, purple seed stain and *Septoria* brown spot are the most prevalent in Brazil (Sautua et al., 2024).

*Cercospora* leaf blight and purple seed stain, although described as two different diseases, are both caused by the same etiological agent, *Cercospora* spp. (Sautua et al., 2024). Recently, studies using multilocus phylogenetic analyses of cercosporoid fungi isolated from soybeans in Argentina, Brazil and the USA confirmed that both *Cercospora* leaf blight and purple seed stain are associated with several cryptic species (Soares et al., 2015). Species from the *Cercospora* genus frequently associated with these diseases in soybeans include *Cercospora kikuchii*, *C. cf. flagellaris*, *C. cf. sigesbeckiae*, and *C. nicotianae* (Soares et al., 2015; Albu et al., 2016; Zivanovic et al., 2021). More recently, molecular analytical methods utilizing five loci from genomic DNA have indicated that *Cercospora* sp. Q is the predominant species causing both diseases in Brazil, followed by *C. kikuchii* and *C. cf. flagellaris*, confirming that multiple *Cercospora* spp. are involved in the late season diseases complex affecting soybean (Fernandes et al., 2024, preprint).

Purple seed stain was first reported in Korea as purple speck or *shihan* (Suzuki, 1921). Subsequent reports emerged from other Asian countries, including Japan, China and Taiwan (Kikuchi, 1924; Han, 1959). Three years later, the first report was documented in the United States (Gardner, 1924) and, in 1981, Argentina reported its first case of infected seeds (Barreto et al., 1981). It is believed that *C. kikuchii* was introduced to South America from Asia, possibly through infected seeds (Imazaki et al., 2006). The initial field description of *Cercospora* leaf blight was published by Walters in 1980 (Sautua et al., 2024).

Currently, the distribution of *C. kikuchii* is worldwide, especially in tropical regions (Wrather et al., 1997). In Brazil, this disease is prevalent in all regions where soybeans are cultivated (Sautua et al., 2024; Almeida et al., 2005), with *C. kikuchii* being the most frequently found fungus in soybean seeds (Henning et al., 2019).

*Septoria* brown spot caused by the fungus *Septoria glycines*, is a highly prevalent disease in all soybean cultivation areas and is typically associated with yield losses (Hartman et al., 2015a; Allen et al., 2017). It often occurs simultaneously with other late season diseases such as *Cercospora* leaf blight (Lin et al., 2021), forming a disease complex (Carmona et al., 2011). *Septoria* brown spot was first described in the United States (Wolf, 1923) and can now be found in other major soybean-producing countries, including Argentina, Brazil and China (Hartman et al., 2015a).

These diseases are economically important and can lead to substantial yield losses (Ward et al., 2015). Yield reductions attributed to late season diseases typically range from 10% to 30% annually, but eventually reaching up to 50%, depending on the environmental conditions during the crop season (Sautua et al., 2024; Martins, 1998).

According to Wrather et al. (1997), *Cercospora* leaf blight and purple seed stain ranked third among the diseases that most contributed to yield losses in Brazil. Recent estimates of yield losses caused by these diseases are not available, primarily due to the difficulty in estimating them, as these diseases typically co-occur with other late season diseases (Sautua et al., 2024). Nonetheless, in the United States, Bandara et al. (2020) estimated economic losses attributed to *Cercospora* leaf blight and purple seed stain between 1996 and 2016 amounted to \$85 million.

Several studies have evaluated yield losses caused by *Septoria* brown spot (Lin et al., 2021). Lim (1979) assessed yield losses of up to 27%, depending on variety, location and whether the plots were inoculated. More recently, in Ohio, Cruz et al. (2010) reported yield losses ranging from 2.5% to 9.5% in naturally occurring fields with different numbers of chlorothalonil applications.

## **2.2 Disease cycle and epidemiology**

*Cercospora* leaf blight, purple seed stain and *Septoria* brown spot are classified as late season diseases due to their symptoms that appear with greater intensity during the advanced reproductive stages of soybean crops, particularly from the

beginning of grain filling and extending into early physiological maturity (R5-R7) (Seixas et al., 2020; Carmona et al., 2010; Carmona et al., 2015).

However, *Cercospora* spp. and *S. glycines* can persist in the area throughout the year, as these fungi survive for extended periods on infested crop residues and infected seeds (Godoy et al., 2022; Lim, 1980), serving as the primary sources of inoculum in the field (Sautua et al., 2024). Additionally, fungi can remain latent in soybean plant tissues from the vegetative stage onward without showing symptoms (Sinclair, 1991).

Conidia from both fungi are carried by wind or raindrops from crop residues, soybean tissues or alternate host tissues from initial and secondary infections (Sautua et al., 2024; Almeida et al., 2019).

Unlike *S. glycines*, which requires rainwater kinetic energy for spore dispersal through the impact of raindrops on pycnidia and conidia removal (Carmona et al., 2017), *Cercospora* species do not depend on water. Their conidia are formed on free conidiophores and are easily dispersed by wind, categorized as dry spores (Kudo et al., 2011; Yeh & Sinclair, 1979).

However, *Cercospora* spp. requires free water to germinate its conidia and initiate parasitism with host tissues (Sautua et al., 2024). The infection process depends on a specific combination of hours of leaf wetness and temperature, including high relative humidity (>90%), temperatures between 20 and 30°C (optimal at 25°C) and several hours of leaf wetness (>18 hours), which create conditions favorable for infection (Schuh, 1991, 1992, 1993).

Since symptoms typically appear at the end of the crop cycle, *Cercospora* leaf blight and purple seed stain is considered a monocyclic disease, once secondary disease cycles are scarce (Carmona et al., 2015). As a result, after the crop is harvested, the pathogen can survive in infested crop residues, infected seeds and alternate hosts and then capable of restarting the disease cycle in the next season (Sautua et al., 2024).

For *Septoria* brown spot, temperatures around 25°C (15°C to 30°C), relative humidity above 90%, foliar wetness lasting 6 to 36 hours and rainfall accompanied by wind are optimal environmental conditions for disease epidemic development and severity increase (Carmona et al., 2017; Lin et al., 2020). These conditions favor conidia germination and germ tube elongation (Schuh and Adamowicz, 1993).

Symptoms of *Septoria* brown spot typically appear approximately two weeks after soybean emergence, with the primary inoculum originating from pycnidia surviving in soybean crop residues in the field. Under favorable conditions, the disease can affect the first trifoliolate leaves and cause defoliation (Godoy et al., 2022; Carmona et al., 2017). In conditions of moisture and rainfall, conidia are dispersed through splash dispersal from lower to upper leaves (Schuh and Adamowicz, 1993). The presence of straw reduces the incidence of brown spot by decreasing the impact of raindrops on the soil and lowering the dispersal of inoculum (Almeida et al., 2019).

### 2.3 Symptomatology

*Cercospora* spp. can cause symptoms on soybean leaves, petioles, stems, pods and seeds (Godoy et al., 2023). Although caused by the same etiological agent, *Cercospora* leaf blight and purple seed stain are historically considered different diseases based on symptomatology (Sautua et al., 2024).

The symptoms of purple seed stain in pods are purple spots that develop and darken as the pathogen sporulates (Sautua et al., 2024). Through infected pods, the fungus reaches the seeds (Godoy et al., 2021). In infected seeds, irregular spots ranging from light pink to dark purple can be small or cover the entire seed coat, occasionally with tegument cracking observed (Sautua et al., 2024; Murakishi, 1951). Despite this, infected seeds may not show visible symptoms (Imazaki et al., 2007).

Purple seed stain is an agronomically and economically important disease because it reduces the commercial value and processing quality of seeds (Lee et al., 2015; Pathan et al., 1989; Roy & Abney, 1976). Additionally, planting infected seeds can increase the incidence of the disease in the field (Imazaki et al., 2007). However, it does not significantly affect the physiological quality or germination rate of the seeds (Henning et al., 2019; Sautua et al., 2024).

The characteristic symptoms caused by *Cercospora* leaf blight are small, dark brownish-red to purple spots with irregular edges, which coalesce and form large dark blight (necrotic tissue) that result in premature defoliation, starting from the leaves in the upper third of the plant (Godoy et al., 2023; Sautua et al., 2024; Chupp, 1954; Ward et al., 2015; Walters, 1980; Sautua, 2021). Necrosis in leaf veins can also be observed (Godoy et al., 2023).

The pathogen reproduces in symptomatic infected tissues by generating asexual spores known as conidia (Sautua et al., 2024). The coloration of the spots caused by both diseases results from the accumulation of the reddish-purple toxin, cercosporin, produced by the fungus, which is a significant factor in pathogenicity and virulence, essential for symptom expression (Godoy et al., 2022; Sautua et al., 2024). Cercosporin strictly depends on light for its biosynthesis and mode of action, triggering the production of reactive oxygen species that cause lysis and death of host cells (Rollins et al., 1993; Daub, 1987; Daub & Ehrenshaft, 2000). This process leads to the release of nutrients into the intercellular space of leaf tissues, thereby promoting fungal growth (Daub & Chung, 2007).

*Septoria* brown spot is characterized by small, irregular necrotic spots ranging from reddish-brown to dark brown, with a necrotic halo (Godoy et al., 2023; Lin et al., 2021). In some cases, symptoms can be observed during the vegetative stage on unifoliolate and the first trifoliolate leaves, causing premature defoliation (Mueller et al., 2016; Cruz et al., 2010; Godoy et al., 2022).

All three diseases often occur simultaneously (Lin et al., 2020). Frequently, symptoms caused by *Cercospora* spp. and *S. glycines* can be indistinguishable in the early stages of the disease in the field (Sautua et al., 2024). Sautua (2021) detected *Cercospora* spp. in soybean leaves sampled in Argentina exhibiting symptoms similar to those caused by *S. glycines* for five consecutive years. Therefore, to ensure accurate identification of pathogens in the field, it is crucial to conduct laboratory tissue analyses for precise diagnosis (Sautua et al., 2024).

## **2.4 Late season diseases management**

Integrated management combines various biological, chemical and cultural control practices to ensure sustainable disease management (Carmona et al., 2017). Effective control of late season diseases during the soybean reproductive stage is crucial to prevent yield loss (Lin et al., 2021).

So far, no commercial soybean varieties have been found to exhibit complete resistance to late season diseases (Sautua et al., 2024, 2020; Carmona et al., 2015; Lim, 1979; Lin et al., 2021). However, some cultivars show varying levels of susceptibility to *C. kikuchii* and *S. glycines*, indicating the possibility of partial soybean

resistance to *Cercospora* leaf blight, purple seed stain and *Septoria* brown spot (Almeida et al., 2005; Walters, 1978; Hartman et al., 2015b; Albu et al., 2016).

Crop rotation with non-legume crops and tillage is recommended to reduce inoculum in the area, as fungi can survive in crop residues (Hartman et al., 2015b; Seixas et al., 2020; Lin, 2021). Other recommended practices include the use of pathogen-free seeds and the treatment of seeds with fungicides (Seixas et al., 2020; Sautua et al., 2020; Carmona et al., 2015). Additionally, the use of cover crops has potential benefits in disease management, as it reduces pathogen splash dispersal caused by rain (Almeida et al., 2019).

The application of fungicides is the most commonly used practice for controlling late season diseases and can significantly reduce disease severity at the end of the season (Godoy et al., 2023; Lin et al., 2021). The application of chlorothalonil and mixtures of demethylation inhibitor (DMI), quinone outside inhibitor (QoI) and succinate dehydrogenase inhibitor (SDHI) between R1 and R6 stages can effectively control these diseases (Cruz et al., 2010; Lin et al., 2021; Sautua et al., 2024). However, several fungicides commonly used to control *Cercospora* leaf blight and purple seed stain have shown reduced efficacy due to the emergence of *C. kikuchii* isolates resistant to QoI and benzimidazole fungicides and with low sensitivity to DMIs (Sautua et al., 2024; Seixas et al., 2020). Mello et al. (2021) reported that about 97% of *Cercospora* spp. isolates collected in different states of Brazil since the 2008 season (n = 56) exhibited G143A mutations in cytochrome b and E198A mutations in  $\beta$ -tubulin, conferring resistance to QoI fungicides and methyl benzimidazole carbamate, respectively.

Thus, the increase in reports of fungicide resistance complicates disease management in various soybean-producing regions and highlights the need for actions to mitigate its impact (Sautua et al., 2021), such as implementing new practices that complement chemical control.

## **2.5 Overview of yield loss models**

In various studies the relationship between yield losses and disease intensity has been explored based on data collected from field experiments (Dalla Lana et al., 2015; Lehner et al., 2017; Santos et al., 2023). In these experiments, different

conditions may lead to varying levels of disease (e.g., fungicide type or number) and the corresponding yield is estimated. Then, models can be fitted to data on the relationship between disease intensity (severity or incidence) and yield (Del Ponte, 2023).

According to Savary et al. (2006), yield losses have been determined to provide quantitative estimates of the impact of disease on specific host crops. For different diseases in soybean crops, the relationships between disease intensity and yield have been explored using data from multiple trials conducted across a range of environmental conditions, which has led to the calculation of the damage coefficients (Dalla Lana et al., 2015; Edwards Molina et al., 2019; Lehner et al., 2017; Barro et al., 2023; Kandel et al., 2020). For instance, Barro et al. (2023) confirmed a negative relationship between the severity of frogeye leaf spot (*Cercospora sojina*) at the R6 development stage and soybean yield using a meta-analytic framework. Their results indicated an overall relative damage coefficient of 0.51% (95% IC = 0.69 - 0.36), meaning that the average reduction in attainable yield is expected to be 51% (36 to 69%) when frogeye leaf spot severity reaches 100%. Similarly, Dalla Lana et al. (2015) identified a significant negative correlation between soybean rust (*Phakopsora pachyrhizi*) severity and yield, with an overall damage coefficient of 0.60% (95% IC = 0.68 - 0.54).

For soybean diseases, the mean slopes of the linear regression models and the damage coefficients determined so far are generally similar across different diseases, with the exception of soybean rust, which shows a higher damage coefficient compared to the others (Table 1). On the other hand, across the different studies, a variable intercept, or the attainable yield (disease-free yield) can be observed over the years and across regions (Table 1).

These results can provide useful information for risk assessment of yield loss (damage) based on disease intensity and highlight the impact of plant diseases on crop productivity (Dalla Lana et al., 2015; Lehner et al., 2017). Additionally, they can clarify which variables might affect the relationship between disease intensity and yield losses (Dalla Lana et al., 2015; Barro et al., 2023; Kandel et al., 2020; Shah & Dillard, 2006).

**Table 1.** Estimates (mean and 95% confidence interval) of linear regression coefficients (intercept and slope), and the respective calculated damage coefficients, obtained from the fit of various meta-analytic regression models to data on five soybean diseases in Brazil and the United States (U.S.).

Disease	Country	Intercept (kg/ha)	Slope (kg/ha/%)	Damage Coefficient (% <sup>-1</sup> )	Reference
Soybean Rust	Brazil	2,977 (2,862 – 3,093)	-18 (-19.4 – -16.6)	0.60 (0.68 – 0.54)	Dalla Lana et al., 2015
Target Spot	Brazil	3,564 (3,376 – 3,753)	-17 (-21.4 – -12.5)	0.48 (0.63 – 0.33)	Edwards Molina et al., 2019
White Mold	Brazil	3,455.7 (3,187.62 – 3,723.88)	-17.24 (-20.56 – -14.28)	0.49 (0.64 – 0.38)	Lehner et al., 2017
Frogeye Leaf Spot	U.S.	3,719.9 (3,403.2 – 4,036.26)	-19.08 (-23.57 – -14.58)	0.51 (0.69 – 0.36)	Barro et al., 2023
Sudden Death Syndrome	U.S.	4,130 (3,922 – 4,339)	-20.9 (-26.4 – -15.4)	0.51 (0.67 – 0.35)	Kandel et al., 2020

### 3 MATERIAL AND METHODS

#### 3.1 Disease and yield data collection and criteria for exclusion of studies

The datasets on disease severity (*Cercospora* leaf blight, purple seed stain and/or *Septoria* brown spot) and yield were obtained from literature sources where the raw data were made available (Godoy et al., 2021; Godoy et al., 2022; Godoy et al., 2023; Godoy et al., 2024). The trials were conducted to compare the efficacy of fungicides in controlling late season diseases in a cooperative network of experiments over four growing seasons (2020-2024), totaling 60 trials conducted in nine states of Brazil (Paraná, Rio Grande do Sul, São Paulo, Tocantins, Bahia, Distrito Federal, Goiás, Mato Grosso do Sul and Mato Grosso). All trials were carried out under the same experimental design and using standardized treatment and evaluation protocols, allowing for the joint summarization of the experiments. The field plots were at least six rows wide and five meters long. The plots were arranged in a randomized complete block design with four replications.

The evaluated fungicide treatments included commercial mixtures of demethylation inhibitors - DMI (difenoconazole, cyproconazole, and tebuconazole), quinone outside inhibitors - QoI (picoxystrobin and trifloxystrobin), succinate dehydrogenase inhibitors - SDHI (benzovindiflupyr), isophthalonitrile (chlorothalonil), inorganic (copper oxychloride) and dithiocarbamate (mancozeb) or DMIs, isophthalonitrile and multi-site inhibitors alone. In the 2021/2022 season, one treatment consisted of a biofungicide with three *Bacillus* species (*B. subtilis*, *B. velezensis* and *B. pumilus*). Up to four applications were performed, varying with the season. Applications began at the pre-row closure stage (development stage V7 - R2), with intervals of 14 to 18 days between applications, with the last application at R4 – R5.3. A CO<sub>2</sub>-pressurized backpack sprayer was used to apply the products with a minimum application volume of 120 L/ha.

The experimental areas were sown at the beginning of the recommended period to reduce the probability of soybean rust incidence, which in turn decreases the incidence of *Cercospora* leaf blight and purple seed stain, as rust causes defoliation of the plant before these diseases occur (Godoy et al., 2021). Disease severity assessments, estimated using a standard area diagram set (Martins et al., 2004), were

conducted between phenological stages R6 and R7 (Fehr & Cavinness, 1977). For the analysis, all assessments were considered as late season diseases, without distinguishing between the diseases. Yield was evaluated by analyzing a minimum central area of 5 m<sup>2</sup> in each plot.

To be included in the analysis, trials had to show a minimum difference of 5 percentage points between the lowest and highest disease severity within the study. This criterion was adapted from previous studies that used 2% and 4% as the minimum range (Madden & Paul, 2009; Duffeck et al., 2020). Additionally, trials where other diseases, such as soybean rust, target spot and powdery mildew exceeding 5% severity were excluded. One study that lacked yield information was also excluded. Consequently, data from 39 studies remained and were used to model the yield-severity relationship (Table 2; Figure S1).

**Table 2.** Municipalities and seasons where trials were conducted to compare the efficacy of fungicides in controlling soybean late season diseases used in this study.

<b>State</b>	<b>Location</b>	<b>Seasons</b>	<b>N. of Trials</b>
MT	Água Boa	2023-2024	1
MS	Bandeirantes	2021-2022, 2022-2023, 2023-2024	3
MT	Campo Novo do Parecis	2023-2024	1
MT	Canarana	2021-2022	1
MS	Chapadão do Sul	2020-2021, 2021-2022, 2022-2023	3
MT	Diamantino	2020-2021, 2022-2023	3
GO	Formosa	2022-2023, 2023-2024	2
RS	Itaara	2022-2023	1
PR	Londrina	2021-2022	1
MT	Lucas do Rio Verde	2022-2023, 2023-2024	2
BA	Luís Eduardo Magalhães	2021-2022	1
MS	Maracaju	2021-2022, 2023-2024	2
MT	Nova Mutum	2023-2024	1
SP	Patrocínio Paulista	2022-2023	1
DF	Planaltina	2021-2022	1
PR	Ponta Grossa	2022-2023, 2023-2024	2
TO	Porto Nacional	2022-2023	1

MT	Primavera do Leste	2020-2021, 2022-2023	2
MT	Querência	2020-2021, 2021-2022, 2022-2023	3
GO	Rio Verde	2020-2021, 2021-2022, 2022-2023, 2023-2024	5
MT	Santa Maria	2023-2024	1
GO	São Miguel do Passa Quatro	2021-2022	1

### 3.2 Severity of late season diseases and yield relationship

In this study, the Pearson correlation coefficient ( $r$ ) and Fisher's transformation ( $Z$ ) were used to study the association between disease severity estimated at the critical point and soybean yield, in addition to the intercept and slope coefficients of the linear regression model estimated for each of the trials (Barro et al., 2023; Duffeck et al., 2020; Madden & Paul 2009). The  $r$  and Fisher's  $Z$  explain the strength of the relationship between disease severity and yield (Dalla Lana, 2015) and was calculated using the `rma.uni` function of the `metafor` package of R (R Core Team, 2020). For these analyses, the sampling variances were estimated using data available at the plot level (four plots of the randomized block design), because they were available.

$Z$  is given by:

$$Z_i = \frac{1}{2} \times \ln\left(\frac{1+r_i}{1-r_i}\right), \quad (1)$$

where  $Z_i$  is the Fisher transformation of the  $i$ -th study ( $i = 1, 2, \dots, n$ ) and  $r_i$  is the Pearson correlation coefficient of the  $i$ -th study.

The sampling variance for each  $k$ -th study is given by:

$$V_Z = \{1 \div (n_i - 3)\}, \quad (2)$$

where  $n_i$  is the number of pairs of late season diseases severity and yield in each  $i$ -th study.

Overall means, 95% confidence intervals (CI 95%) and 95% prediction intervals were also calculated (Viechtbauer, 2010). Heterogeneity among true effect sizes were assessed based on the significance of Cochran's Q test and the  $I^2$  index, which measures the extent of heterogeneity of true effect sizes (Higgins & Thompson, 2002).

The intercept ( $\beta_0$ ) and slope ( $\beta_1$ ) coefficients of the linear regression model fitted to the data were calculated using a random-effects meta-analysis using the `rma` function from the `metafor` package (Viechtbauer, 2010). When performing the meta-analysis, the goal is to combine estimates from various studies or trials into a single overall estimate (Del Ponte, 2023).

Moderator variables that could explain at least part of the heterogeneity in the true effects were included as fixed effects and expanded the model from a random to a mixed effects model (Madden & Paul, 2009). All moderator variables were categorical, including disease pressure (low severity =  $\leq 35\%$  and high severity =  $> 35\%$ ), yield class (low =  $\leq 3,745$  kg/ha and high =  $> 3,745$  kg/ha), region (field trials conducted in locations below  $20^\circ\text{S}$  were classified as southern, and the others as northern), altitude ( $< 635$  or  $\geq 635$  m above sea level), and year. The categories for altitude, disease pressure, and yield classes were defined based on the median of the data. Severity was defined based on the untreated control data from the field trials.

The among-study variance was estimated using maximum likelihood, and the mean effect was estimated using weights based on the among-study variance and the within-study variance, with the latter being held fixed for each study (Madden & Paul, 2011). Wald-type tests and 95% confidence intervals were obtained assuming normality.

### 3.3 Relative yield loss estimation

The intercept ( $\beta_0$ ) and slope ( $\beta_1$ ) represent, respectively, the attainable yield when disease severity is zero (kg/ha) and the yield reduction per unit increase in % disease severity (kg/ha/%). As damage functions are commonly reported in relative terms (percent increase in yield loss or percent yield reduction) and for comparison purposes with other studies, the damage coefficient were calculated by dividing the estimated slope ( $\beta_1$ ) by the estimated intercept ( $\beta_0$ ) and multiplying by 100 (Barro et al., 2023; Dalla Lana et al., 2015; Lehner et al., 2017; Madden & Paul, 2009).

### 3.4 Economic damage threshold

The economic threshold (EDT) was calculated using the Mumford and Norton (1894) formula, modified for plant diseases by Reis (Reis et al., 2002; Casa et al., 2009; Carmona et al., 2015):

$$EDT = \frac{C}{S_p \times D_c} \times \lambda, \quad (3)$$

where EDT = disease intensity (% in disease severity); C = cost of control (USD/ha);  $S_p$  = soybean price (USD/ton);  $D_c$  = damage coefficient (standardized to metric tons and multiplied by the the attainable yield);  $\lambda$  = fungicide efficacy.

Using Equation 3, a range of EDT was calculated based on the estimated damage coefficient standardized to metric tons (0.0049) (this study) and various values of attainable yield (mean = 4.6 ton/ha, SD = 0.79 ton/ha) (this study) and fungicide efficacy (mean = 54%, SD = 10%) (Godoy et al., 2024). The cost with one application of fungicides (fungicide price + operational costs) was fixed at 25 USD/ha, an estimate for the state of Mato Grosso State for the 2023/24 season (João Ascari - personal communication). The price of the ton of soybean was estimated at a fixed value of 393.22 USD/ton, based on the estimate for August 2024 (source: <https://www.noticiasagricolas.com.br/cotacoes/soja>).

The raw data and R codes for conducting all analyses are freely available at <https://github.com/anacccarv/yield-loss-lsd>.

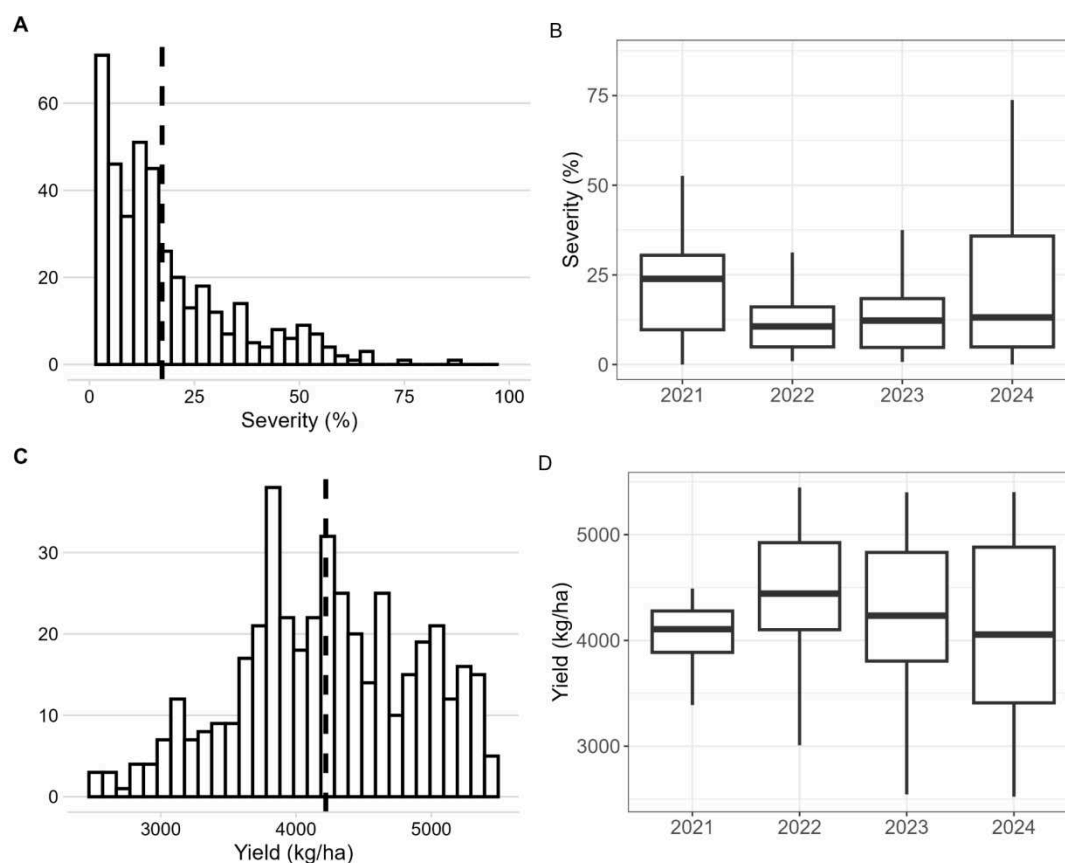
## 4 RESULTS

### 4.1 Study-level variables

In the majority of the trials in Brazil the disease reported by the researchers was late season diseases, as a complex of diseases where *Cercospora* leaf blight is the most prevalent followed by *Septoria* brown spot (Cláudia Godoy, personal communication). *Cercospora* spp. alone was reported in six trials (trials 1, 2, 30, 31, 35, and 38), while *Septoria glycines* alone was reported in two trials (trials 3 and 14). The results showed a wide variation in late season diseases severity across the different trials, with values ranging from 0 to 86.25% (mean = 17.29%). The severity distribution was slightly skewed (Figure 1A). Over the years, late season diseases severity fluctuated, with the lowest values observed in the 2021/2022 growing season (S = 12.39%) and the highest in the 2020/2021 growing season (S = 22.09%) (Figure 1B). For soybean yield, there was considerable variation across the trials, ranging from 2,523 to 5,446 kg/ha (mean = 4,220 kg/ha). However, the distribution of the data was more symmetrical (Figure 1C). Yield also varied over the years, with the lowest values recorded in the 2020/2021 growing season (Y = 4,064.35 kg/ha) and the highest in the 2021/2022 growing season (Y = 4,456.83 kg/ha) (Figure 1D). Overall, there was a slight decrease in the yield as the severity of late season diseases increased (Figure S2).

### 4.2 Association between severity and yield

Pearson correlation coefficients ( $r$ ) ranged from -0.895 to 0.003 with only one instance of a positive correlation (Figure 2A). Fisher's distribution coefficients ( $Z$ ) varied from -1.444 to 0.003 (Figure 2B), with an estimated mean of -0.55 (95% CI = -0.65 to -0.45). This corresponds to an estimated inverse-transformed correlation coefficient across all studies of -0.50 (95% CI = -0.57 to -0.42) (Table 3).



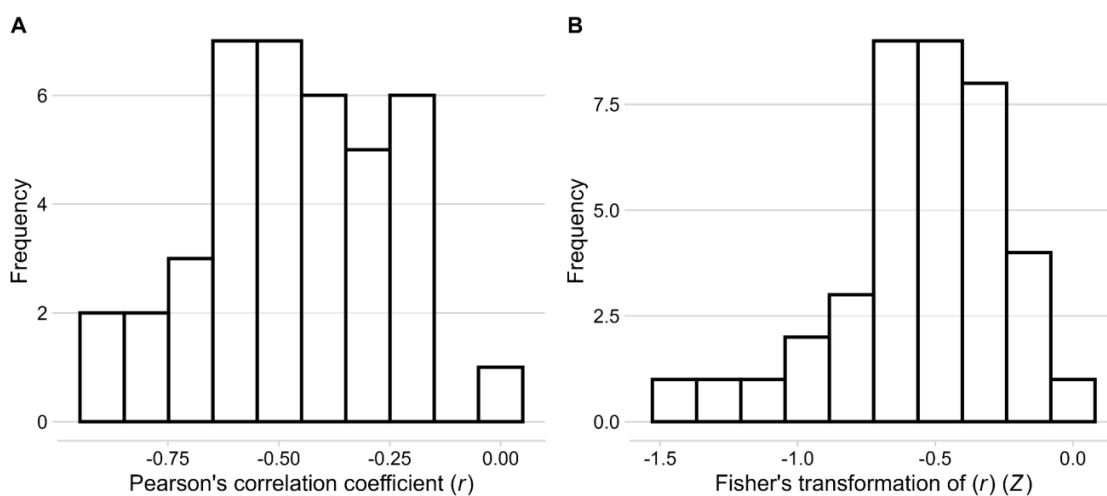
**Figure 1.** **A.** Histogram for severity (%) data. Black dashed lines represent the mean. **B.** Boxplot summarizing the distribution of severity of each year of studies used to model the yield-severity relationship for the late season diseases on soybean. **C.** Histogram for soybean yield (kg/ha) data. Black dashed lines represent the mean. **D.** Boxplot summarizing the distribution of soybean yield of each year of studies used to model the yield-severity relationship for the late season diseases on soybean.

The null hypothesis of homogeneity for Fisher's  $Z$  was rejected ( $Q = 156.73$ , d.f. = 38,  $P < 0.0001$ ), indicating significant statistical heterogeneity among the studies. Additionally, the relationship between late season diseases severity and yield was significantly different from zero, as confirmed by the  $Q$  test ( $P < 0.0001$ ) (Table 1). The variability between studies ( $\tau^2$ ), estimated using a random-effects model meta-analysis, was high ( $\tau^2 = 0.075$ ,  $SE = 0.0229$ ), as confirmed by the significance of the  $Q$  test and the high  $I^2$  values (75.81%).

Regarding the regression coefficients, the intercept ( $\square_0$ ) which corresponds to the yield achievable in the absence of disease, ranged from 2,745.79 to 7,012.62 kg/ha, with a population mean of 4,598 kg/ha (Figure 3A, D). The distribution of  $\beta_1$  ranged from -81.57 to 0.49 kg/ha, with a population mean of -24.03 for each

percentage increase in severity (Figure 3B, D). Negative values were observed in over 97% of the trials, with only one trial showing a positive slope (Figure 3). The estimates for the population mean of the intercept and slope were  $\beta_0 = 4,589.06$  kg/ha (SE = 123.9 kg/ha) and  $\beta_1 = -22.58$  kg/ha for each percent unit of severity (SE = 2.1), respectively (Table 2; Figure 3E), according to the random-effects model. Both parameters were statistically significantly different from 0 ( $P < 0.001$ ) based on the Q test. The respective 95% confidence intervals (CI) and 95% prediction intervals for the intercept, slope, and the transformed and back-transformed Pearson correlation coefficients from the random-effects model are presented in Table 3.

None of the moderator variables tested individually as fixed effects significantly affected the slope ( $\beta_1$ ) ( $P > 0.19$ ) according to a Wald-type test. However, the moderator variables such as disease pressure, yield class and altitude significantly affected the intercept ( $\beta_0$ ) ( $P < 0.014$ ). The study-specific parameters estimated for  $\beta_0$  varied depending on the moderator variable. For yield class, the estimates were 4,128.90 kg/ha (SE = 130.92) and 5,107.47 kg/ha (SE = 192.03) for classes  $\leq 3,745$  and  $> 3,745$ , respectively. For disease pressure, the values were 4,323.03 kg/ha (SE = 158.41) and 4,897.90 kg/ha (SE = 233.47) for classes  $\leq 35\%$  and  $> 35\%$ . Regarding altitude, the estimates were 4,290.96 kg/ha (SE = 161.44) for altitudes  $< 635$  m and 4,897.23 kg/ha (SE = 230.72) for altitudes  $\geq 635$  m (Table 4). Since the moderator variables had no effect on  $\beta_1$ , we consider the slope from the random-effects model as the general slope.



**Figure 2. A.** Frequency distribution of Pearson's correlation coefficient ( $r$ ) for the 39 field trials used to model the yield-severity relationship. **B.** Distribution of Fisher's transformation of coefficient  $r$  ( $Z$ ) in the same trials.

**Table 3.** Means, related statistics and heterogeneity measures of the transformed correlation coefficients ( $Z$ ) and back-transformed Pearson correlation coefficients ( $r$ ) and intercept ( $\beta_0$ ) and slope ( $\beta_1$ ) of the linear regression for the relationship between late season diseases severity and soybean yield, based on a random-effects model.

Effect-size <sup>e</sup>	Statistics <sup>a</sup>								Heterogeneity <sup>b</sup>	
	k <sup>c</sup>	Mean	SE	CI <sub>L</sub>	CI <sub>U</sub>	PI <sub>L</sub>	PI <sub>U</sub>	P-value	r <sup>2</sup>	I <sup>2</sup> (%)
<b>Correlation</b>										
$Z$	39	-0.55	0.0506	-0.6479	-0.4495	-1.0948	-0.0026	0.0001	0.0751	75.81
$r$	39	-0.50	----	-0.5702	-0.4215	-0.7986	-0.0026	----	----	----
<b>Linear regression</b>										
Intercept ( $\beta_0$ )	39	4,598.0	123.88	4,346.2	4,831.8	3,074.0	6,104.1	0.0001	582,167.4	99.08
Slope ( $\beta_1$ )	39	-22.58	2.06	-26.62	-18.55	-43.85	-1.31	0.0001	113.48	83.80

<sup>a</sup> Standard error (SE); lower (CI<sub>L</sub>) and upper (CI<sub>U</sub>) limits of the 95% confidence interval; lower (PI<sub>L</sub>) and upper (PI<sub>U</sub>) limits of the 95% prediction interval;

<sup>b</sup> Between-studies variance estimates (r<sup>2</sup>) and I<sup>2</sup> statistic;

<sup>c</sup> Total number of trials used in analysis.

### 4.3 Model-predicted yield losses

Based on the overall mean of the intercept ( $\beta_0 = 4,589.06$  kg/ha) and the slope ( $\beta_1 = -22.58$  kg/ha) estimated by the random-effects model, the overall relative damage coefficient was estimated at -0.49% (95% CI = -0.61 to -0.38), indicating that a percentage increase in late season diseases severity would result in a 0.49% decrease in soybean yield. We also calculated the relative yield loss for severity values of 10%, 25%, 50%, and 75%. The estimated yield reductions would be 4.9%, 12.25%, 24.5%, and 36.75%, respectively. To achieve a relative yield of 80%, corresponding to a 20% reduction in yield, the severity of late season diseases would need to reach approximately 40.6% (Figure 3F).

Although the effect of moderator classes was not significant in  $\beta_1$ , the calculated damage coefficient values varied among the different classes. For the yield class, the coefficients were -0.55% for the  $\leq 3,745$  and -0.44% for the  $> 3,745$  classes. For disease pressure, the values were -0.52% for the  $\leq 35\%$  and -0.46% for the  $> 35\%$  classes. Regarding altitude, the coefficients were -0.53% for altitudes  $< 635$  and -0.46% for altitudes  $\geq 635$ .

**Table 4.** Means and related statistics of the intercept ( $\beta_0$ ) of the meta-regression model fitted for the relationship between the severity of late season diseases in soybean and crop yield, for which the inclusion of the moderator variable in the model was statistically significant ( $P < 0.01$ ).

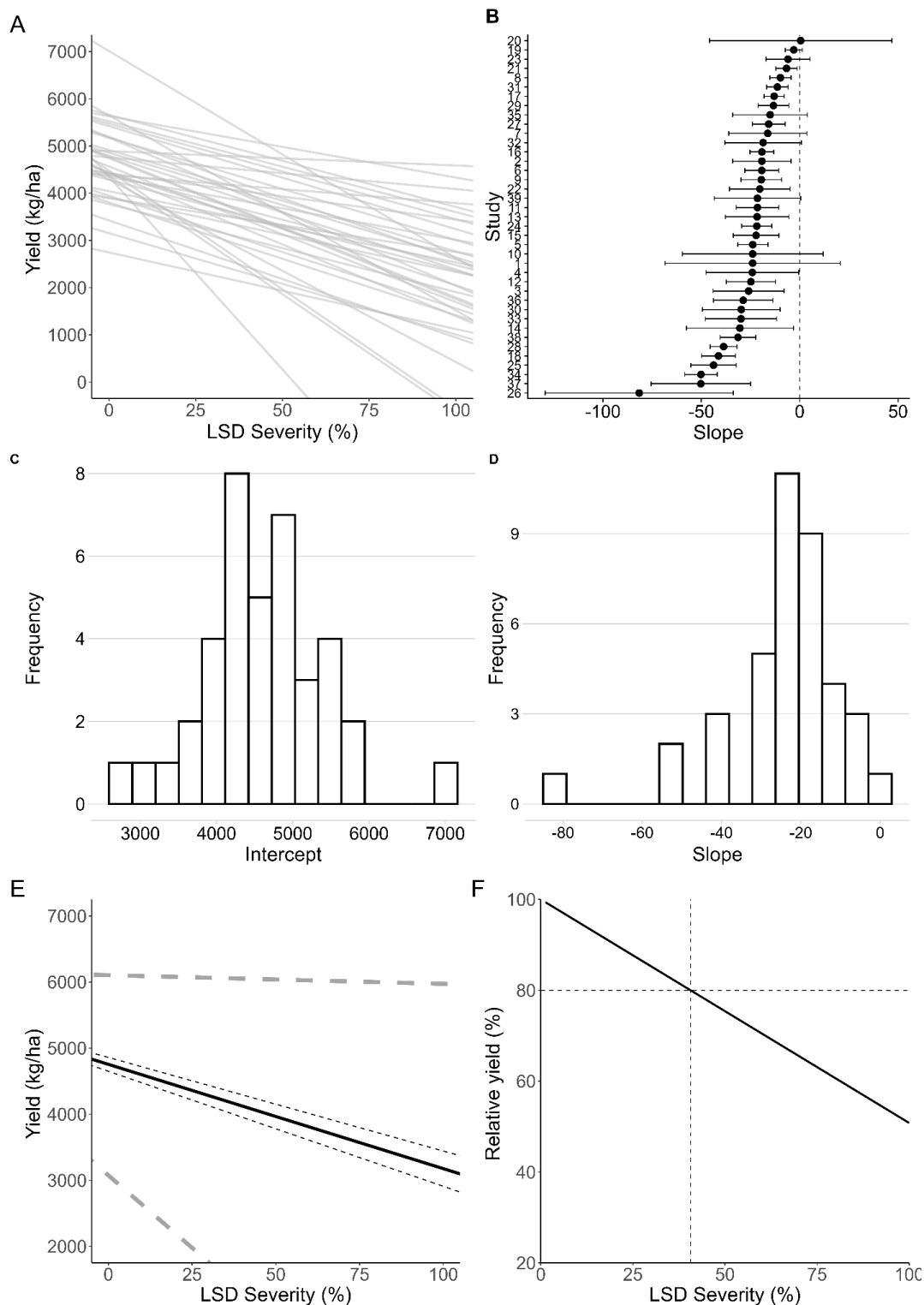
	Estimated intercept ( $\beta_0$ )				
	k <sup>a</sup>	P value	Mean	CI <sub>L</sub> <sup>b</sup>	CI <sub>U</sub> <sup>b</sup>
<b>Moderator effect</b>					
<b>Yield class</b> ( $P = < 0.0001$ )					
≤3,745 kg/ha	21	< 0.0001	4,128.90	3,872.29	4,385.51
>3,745 kg/ha	18	< 0.0001	5,107.47	4,474.50	5,740.44
<b>Disease pressure</b> ( $P = < 0.0137$ )					
≤35%	21	< 0.0001	4,323.03	4,020.56	4,624.93
>35%	18	0.0114	4,897.90	4,150.27	5,645.52
<b>Altitude</b> ( $P = < 0.0001$ )					
<635 m	20	< 0.0001	4,290.96	3,974.53	4,607.38
≥635 m	19	0.0086	4,897.23	4,128.61	5,665.86

<sup>a</sup> Number of trials per level of the moderator variable;

<sup>b</sup> Lower (CI<sub>L</sub>) and upper (CI<sub>U</sub>) limits of the 95% confidence interval.

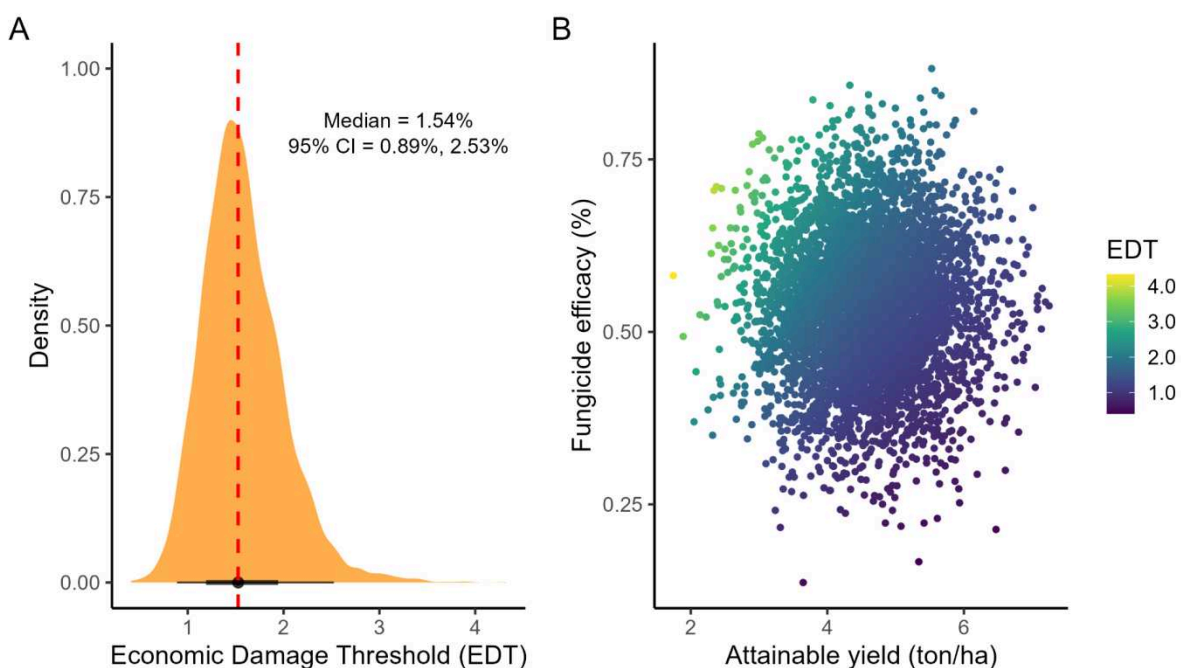
#### 4.4 Economic damage threshold

For fungicide efficacy ( $\lambda$ ) ranging from 14% to 88%, the economic damage threshold (EDT) varied between 0.41% and 4.33%, with an average EDT of 1.57% corresponding to a mean fungicide efficacy of 54% (Figure 4A). In general, the higher the attainable yield and the higher the fungicide efficacy, the lower the EDT values, and vice-versa (Figure 4B). For example, in a hypothetical scenario with the mean values for the attainable yield (4.6 tons/ha) and mean of fungicide efficacy (55%), the EDT would be 1.56% severity. In comparison, for an attainable yield of 3.2 tons/ha with the same fungicide efficacy, the EDT would increase to 2.19% severity.



**Figure 3.** **A.** Study-specific prediction regression lines (gray lines) from a simple linear model fitted using the 39 field trials conducted in the study of the relationship between late season diseases severity and soybean yield. **B.** Forest plot showing the distribution of the  $\beta_1$ . Black circles represent the value of  $\beta_1$  (kg/ha) in each individual study and horizontal bars indicate the lower and upper 95% confidence interval limits. **C.** Frequency distribution of the intercept ( $\beta_0$ ) ( $k = 39$ ). **D.** Frequency distribution of the slope ( $\beta_1$ ) ( $k = 39$ ). **E.** Population-average prediction (solid black line) with the corresponding 95% confidence interval (dashed black lines) and 95% prediction

interval (dashed gray lines). **F.** Relative yield loss based on estimated parameters from the meta-analysis of the relationship between late season diseases severity and soybean yield. The horizontal dashed line represents a 20% yield loss, while the vertical dashed line indicates the level of severity at which a 20% yield loss occurred.



**Figure 4. A.** Density of economic damage threshold (EDT) values ( $n = 5,000$  simulations) considering a fixed value of control cost ( $C = 25$  USD/ha), a fixed value of soybean price ( $S_p = 393.22$  USD/ton) and variable values of fungicide efficacy (mean = 54%, SD = 10%) and attainable yield (mean = 4.6 ton/ha, SD = 0.79 ton/ha). Red dashed line represents the median. **B.** Variation in the EDT values based on the variation in fungicide efficacy (%) and attainable yield (ton/ha).

## 5 DISCUSSION

Despite the use of fungicides, a relatively low efficacy (~50%) has been reported in controlling the late season diseases complex in Brazil which includes *Cercospora* leaf blight, purple seed stain and *Septoria* brown spot; such level of efficacy prevents only partially the yield losses due to this disease complex (Godoy et al., 2023). The presence of these diseases in nearly all soybean-producing regions in Brazil underscores the need for studies that investigate the relationship between disease intensity and crop yield. This is the first study to apply meta-analytic methods to analyze data from different locations and growing seasons related to late season diseases, similar to previous studies that investigated the relationship between disease intensity and yield in other soybean diseases (Barro et al., 2023; Lehner et al., 2017; Dalla Lana et al., 2015; Edwards Molina et al., 2019; Kandel et al., 2020). Our results confirm that late season diseases, particularly the complex of *Cercospora* leaf blight, purple seed stain and *Septoria* brown spot, is an important yield-limiting factor for soybean. A moderate but significant negative correlation was found between late season diseases severity and yield, contrasting with the findings by Carmona et al. (2015), who reported no correlation between these two variables in 19 field experimental trials conducted during five seasons (2007-08 to 2011-12) in Argentina. Additionally, a significant negative slope obtained through random-effects meta-analytic modeling using an expressive number of trials ( $n = 39$ ) confirmed the negative linear relationship between late season diseases severity and soybean yield.

For the attainable yield (population-average intercept), or when plots are disease-free, our estimate was higher (4,598.06 kg/ha) than estimates from other similar studies in Brazil involving other diseases. For example, Dalla Lana et al. (2015) assessed the damage coefficient for soybean rust in 231 uniform field trials conducted over nine growing seasons and found an intercept estimate of 2,977 kg/ha. Lehner et al. (2017) evaluated the damage coefficient for white mold in 36 uniform field experiments conducted over four growing seasons and reported an intercept estimate of 3,455.70 kg/ha. Conversely, Edwards Molina et al. (2019), in a meta-analysis of target spot with 41 individual experiments, found an estimate of 3,564 kg/ha. The increased the attainable yield over time may be attributed to the fact that, over the years, more productive and stress-resistant cultivars (both biotic and abiotic stresses)

have become available on the market (Zanon et al., 2015; Batista et al., 2024; Gomes, 2023).

The obtained damage coefficient indicated that for each unit increase in disease severity, yield decreases by 0.49%. In other words, when the maximum severity is observed (late season disease severity = 100%), a 49% reduction in soybean yield is expected on average. However, although the damage coefficient for late season diseases is high, the severity observed in the field for these diseases is usually not (Godoy et al., 2021, 2022, 2023, 2024). A practical example of this situation would be that, considering the average late season diseases severity of 17.29%, the yield reduction would be approximately 8.5%. If the attainable yield in this same scenario were 4,500 kg/ha, this would result in a reduction of 382.5 kg/ha.

This damage coefficient is similar to those reported for other soybean diseases, such as target spot (0.48 %<sup>-1</sup>), white mold (0.49 %<sup>-1</sup>), frogeye leaf spot (0.51 %<sup>-1</sup>), and sudden death syndrome (0.51 %<sup>-1</sup>) (Edwards Molina et al., 2019; Lehner et al., 2017; Barro et al., 2023; Kandel et al., 2020). However, our estimates are lower than the overall damage coefficient estimated for soybean rust (0.60 %<sup>-1</sup>) (Dalla Lana et al., 2015), which may be related to the early defoliation of the crop induced by the latter and reduced photosynthetically active area, enhancing the damage to the crop. This confirms soybean rust as a more damaging foliar disease of soybeans (Meira et al., 2020).

Although the moderator variables defined in this study did not influence the slope, the intercept values differed between the studies according to the classes. As expected, the intercepts varied among trials representing low or high yield. Similar effects, where only intercepts and not slopes were affected by yield class, were also observed by Barro et al. (2023), in a study that summarized the relationship between *Cercospora sojina* and soybean yield across 39 studies conducted over nine years in the U.S. The significant effect of altitude as a moderator may be related to the climatic conditions that either favor or hinder soybean development. In Brazil, altitude is associated with differences in temperature and precipitation (Alliprandini et al., 2009). Because the soybean growth cycle and vegetative development are influenced by temperature, altitude differences tend to alter plant phenology, even when photoperiod conditions are equivalent (Bergamaschi, 2007).

Given that the intercept values varied across studies due to moderator variables, the magnitude of the damage coefficient, which is a ratio between  $\square_1$  and  $\square_0$ ,

differed among the various classes. For example, when an attainable yield > 3,745 kg/ha is expected, the damage coefficient calculated in our study (-0.44%) was lower than the overall damage coefficient (-0.49%) but close to the damage coefficient for frogeye leaf spot in soybean, calculated by Barro et al. (2023) for the high-yield class. In soybeans, *Cercospora* species cause two notable diseases: frogeye leaf spot, caused by *Cercospora sojina*, and *Cercospora* leaf blight/purple seed stain, which is mainly caused by a complex of *Cercospora* species and is part of the late season diseases complex (Sautua et al., 2024). While purple seed stain can cause symptoms on pods and seeds, leading to reduced product quality, both frogeye leaf spot and *Cercospora* leaf blight primarily affect the plant by reducing the photosynthetic rate (Savary et al., 2012). This shared mechanism of damage may explain the similar values observed in the damage coefficient for these diseases.

The most rational and recommended criterion for determining the ideal time to start fungicide applications is the economic damage threshold (EDT) (Reis et al., 2018; Madden et al., 2007). For late season diseases in soybean, the threshold value increased as control efficacy increased and was influenced by the attainable yield, which is expected given its formulation. The higher the attainable yield, the lower the EDT values, regardless of fungicide efficacy. Given that the control cost for late season diseases was relatively low (25 USD/ha), it is worthwhile to control the diseases even when the severity (disease intensity) in the field is low, as it corresponds to an economic loss that equals the cost of controlling the disease (Del Ponte, 2023). It is important to emphasize that the thresholds obtained in this study are just examples, calculated with the values previously indicated, and can vary depending on potential grain yield, fungicide application costs, and soybean prices (Barro et al., 2023).

For the most likely scenario that we investigated, the EDT can be considered relatively low (1.58 % severity), which suggests that the sprays should commence at a very low level or when the first symptoms of the disease are noticed. It is recognized that severity, compared to incidence, is a more difficult variable to visually assess (Del Ponte et al., 2023). Amanat (1976) observed that the precision of severity estimates was low when symptoms consisted of small lesions, and raters tended to overestimate such symptoms. Sherwood et al. (1983) and Hock et al. (1992) also showed that overestimation was greater at low disease severities. In general, visual estimates by raters are not particularly accurate when assessing smaller lesions (Bock et al., 2022). The quality of the assessment of any disease variable is extremely important and can

impair decision-making for the timing of fungicide applications, affecting control effectiveness. The possibility of identifying the disease as early and quickly as possible can provide greater chances of success in a disease management program (Negrisoli et al., 2022). As many of the fungicides recommended for controlling late season diseases act preventively, aiming to prevent any incidence and proliferation of the disease in the field, in general, preventive applications can be adopted for controlling these diseases due to the low EDT values. This information should be implemented within an integrated disease management system, always prioritizing the rotation of fungicides with different modes of action (Godoy et al., 2024), with the aim of avoiding selection pressure for resistant fungal populations. It is also crucial to emphasize that unnecessary applications not only increase costs but also accelerate the selection for resistance to site-specific fungicides (Reis et al., 2018).

In conclusion, we confirmed a significant negative linear relationship between soybean yield and the severity of *Cercospora* leaf blight, purple seed stain and *Septoria* brown spot, diseases that are the main components of the late season diseases complex that prevails in Brazil. The damage coefficient estimated in our study was based on a dataset of trials conducted to compare the efficacy of fungicides over four growing seasons, across different locations and under various conditions. These models can provide broader estimates of yield loss in relation to late season diseases severity. However, the significant variability observed, which might be related to unknown factors, may hinder precise predictions of actual yield. Nevertheless, the results of this study can offer valuable information for regional risk assessment of potential yield loss if late season diseases severity is measured on-site. Moreover, the findings of this study could enhance integrated disease management programs by informing fungicide use based on disease monitoring and epidemiological insights. Given that *Cercospora* leaf blight and purple seed stain are more predominant in Brazil, further research is needed to understand the specific impact of each disease within the late season diseases complex on soybean yield, as well as the relevance of these diseases under various management scenarios.

## 6 REFERENCES

- Albu, S., Schneider, R.W., Price, P.P., Doyle, V.P. (2016). *Cercospora* cf. *flagellaris* and *Cercospora* cf. *sigesbeckiae* are associated with *Cercospora* leaf blight and purple seed stain on soybean in North America. *Phytopathology*, 106, 1376–1385.
- Allen, T. W., Bradley, C. A., Sisson, A. J., Byamukama, E., Chilvers, M. I., Coker, C. M., Collins, A. A., Damicone, J. P., Dorrance, A. E., Dufault, N. S., Esker, P. D., Faske, T. R., Giesler, L. J., Grybauskas, A. P., Hershman, D. E., Hollier, C. A., Isakeit, T., Jardine, D. J., Kelly, H. M., Kemerait, R. C., Kleczewski, N. M., Koening, S. R., Kurle, J. E., Malvick, D. K., Markell, S. G., Mehl, H. L., Mueller, D. S., Mueller, J. D., Mulrooney, R. P., Nelson, B. D., Newman, M. A., Osborne, L., Overstreet, C., Padgett, G. B., Phipps, P. M., Price, P. P., Sikora, E. J., Smith, D. L., Spurlock, T. N., Tande, C. A., Tenuta, A. U., Wise, K. A., Weather, J. A. (2017). Soybean yield loss estimates due to diseases in the United States and Ontario, Canada, from 2010 to 2014. *Plant Health Prog.* 18 (1):19–27.
- Alliprandini, L. F., Abatti, C., Bertagnolli, P. F., Cavassim, J. E., Gabe, H. L., Kurek, A., Matsumoto, M. N., Oliveira, M. A. R., Pitol, C., Prado, L. C., Steckling, C. (2009). Understanding soybean maturity groups in Brazil: environment, cultivar classification, and stability. *Crop science*, 49(3), 801-808.
- Almeida, Á. M. R., Piuga, F. F., Marin, S. R. R., Binneck, E., Sartori, F., Costamilan, L. M., Teixeira, M. R. O., Lopes, M. (2005). Pathogenicity, molecular characterization, and cercosporin content of Brazilian isolates of *Cercospora kikuchii*. *Fitopatologia Brasileira*, 30, 594-602.
- Almeida, A. M. R., Sibaldelli, R. N. R., Lopes, I. O. N., Oliveira, M. C. N., Farias, J. R. B. (2019). Horizontal and vertical droplet dispersion mimicking soybean-*Septoria glycines* pathosystem. *European Journal of Plant Pathology*, 154, 437-443.
- Amanat, P. (1976). Stimuli affecting disease assessment. *Agriculturae Conspectus Scientificus*, 39, 27-31.
- Balbinot Junior, A. A., Nepomuceno, A. L., Hirakuri, M. H., dos Santos, J. C. F., Debias, H., Coelho, A. E. (2022). Analysis of soybean production, cultivated area, productivity and production stability in Brazilian states over 25 crop seasons (1996/1997 to 2020/2021).
- Bandara, A. Y., Weerasooriya, D. K., Bradley, C. A., Allen, T. W., Esker, P. D. (2020) Dissecting the economic impact of soybean diseases in the United States over two decades. *PLoS One*, 15, e0231141.
- Barreto, D.E., Rossi, L.A., Traut, E., Fortugno, C. (1981) Hongos patógenos en semillas de soja. In: IV Jornadas Fitosanitarias Argentinas. Córdoba: UNC, 27.
- Barro, J. P., Del Ponte, E. M., Allen, T., Bond, J. P., Faske, T. R., Hollier, C. A., Kandel, Y. R., Mueller, D. S., Kelly, H. M., Kleczewski, N. M., Ames, K. A., Price, P., Sikora, E. J., Bradley, C. A. (2023). Meta-Analytic modeling of the severity–yield relationships in soybean frogeye leaf spot epidemics. *Plant Disease*, 107(11),

3422-3429.

- Batista, A. A. M., Fontanela, E., dos Santos Cunha, V., da Conceição, C. G., Gautério, G. R., Jaques, L. B. A., Saldanha, A. P. (2024). Evolução do cultivo de soja em terras baixas: Um panorama na visão dos produtores. Seven Editora, 28-49.
- Bergamaschi, H. (2007). O clima como fator determinante da fenologia das plantas. In: Fenologia: ferramenta para conservação, melhoramento e manejo de recursos vegetais arbóreos. Colombo: Embrapa Florestas, 1, 291-310.
- Bock, C. H., Chiang, K. S., Del Ponte, E. M. (2022). Plant disease severity estimated visually: a century of research, best practices, and opportunities for improving methods and practices to maximize accuracy. *Tropical Plant Pathology*, 47(1), 25-42.
- Borenstein, M., Hedges, L. V., Higgins, J. P. T., Rothstein, H. R. (2009). *Introduction to Meta-Analysis*. John Wiley & Sons, Chichester, UK.
- Carmona, M., Moschini, R., Cazenave, G., Sautua, F. (2010). Relación entre la precipitación registrada en estados reproductivos de la soja y la severidad de *Septoria glycines* y *Cercospora kikuchii*. *Tropical Plant Pathology*, 35, 71–78.
- Carmona, M., Reis, E., Sautua, F. (2017) Sustainable chemical control of main soybean diseases in South America. In: Fletcher, B. (Ed.) *Soybeans: cultivation, nutritional properties and effects on health*. New York: Nova Science Publishers Inc, pp. 203–245.
- Carmona, M., Sautua, F., Perelman, S., Reis, E. M., Gally, M. (2011). Relationship between late soybean diseases complex and rain in determining grain yield responses to fungicide applications. *Journal of phytopathology*, 159(10), 687-693.
- Carmona, M. A., Sautua, F.J., Perelman, S., Gally, M., Reis, E. M. (2015). Development and validation of a fungicide scoring system for management of late season soybean diseases in Argentina. *Crop Protection*, 70, 83–91.
- Casa, R. T., Reis, E. M., Casa, M. (2009). Critério: limiar de dano econômico (LDE) e quantificação de danos. Critérios indicadores do momento para aplicação de fungicidas visando ao controle de doenças em soja e trigo. Ed. Aldeia Norte, Passo Fundo, RS, Brasil. pp:66-78.
- Chupp, C. (1954) *A monograph of the fungus genus Cercospora*. Ithaca, NY: Cornell University Press.
- Cruz, C. D., Mills, D., Paul, P. A., Dorrance, A. E. (2010). Impact of brown spot caused by *Septoria glycines* on soybean in Ohio. *Plant disease*, 94(7), 820-826.
- Dalla Lana, F., Ziegelmann, P. K., Maia, A. D. H., Godoy, C. V., Del Ponte, E. M. (2015). Meta-analysis of the relationship between crop yield and soybean rust severity. *Phytopathology*, 105(3), 307-315.
- Daub, M. E., Chung, K. R. (2007). Cercosporin: a photoactivated toxin in plant disease. *Journal*, Saint Paul, USA. Online. DOI: 10.1094/APSnetFeature/2007-0207.

- Daub, M. E., Ehrenshaft, M. (2000). The photoactivated *Cercospora* toxin cercosporin: contributions to plant disease and fundamental biology. *Annual Review of Phytopathology*, 38, 461–490.
- Daub, M. E. (1987). The fungal photosensitizer cercosporin and its role in plant disease. *ACS Symposium Series*, 339, 271–280.
- Del Ponte, E. M. (2023). R for Plant Disease Epidemiology (R4PDE). Author. <https://r4pde.net>
- Del Ponte, E. M., Mahlein, A. K., & Bock, C. H. (2024). Plant disease quantification. In *Agrios' Plant Pathology* (pp. 211-225). Academic Press.
- Duffeck, M. R., dos Santos Alves, K., Machado, F. J., Esker, P. D., Del Ponte, E. M. (2020). Modeling yield losses and fungicide profitability for managing *Fusarium* head blight in Brazilian spring wheat. *Phytopathology*, 110(2), 370-378.
- Edwards Molina, J. P., Paul, P. A., Amorim, L., da Silva, L. H. C. P., Siqueri, F. V., Borges, E. P., Campos, H. D., Venancio, W. S., Meyer, M. C., Martins, M. C., Balardin, R. S., Carlin, V. J., Grigolli, J. F. J., Belufi, L. M. R., Nunes Junior, J., Godoy, C. V. (2019). Effect of target spot on soybean yield and factors affecting this relationship. *Plant Pathology*, 68(1), 107-115.
- Fehr, W., Caviness, C. (1977). Stages of soybean development.
- Fernandes, A. F. D., Stilgenbauer, S., Stammler, G., Brahm, L., von Tiedemann, A. (2024). Identification of *Cercospora* species associated with the late cycle disease complex of soybean in Brazil. *Research Square* [Preprint.] August 14, 2024. Accessed 2024 September 09. Available from: <https://doi.org/10.21203/rs.3.rs-4730506/v1>.
- Gardner, M.W. (1924) Indiana plant diseases. *Proceedings of the Indiana Academy of Sciences*, 35, 237–257.
- Godoy, C. V., Utiamada, C. M., Meyer, M. C., Campos, H. D., Lopes, I. O. N., Mochko, A. C. R., Farias, A., Muhl, A., Tomen, A., Dias, A. R.; Sichoeki, D., Konageski, F. T., Araújo Júnior, I. P., Roy, J. M. T., Bonani, J. C., Nunes Junior, J., Kudlawiec, K., Sato, L. N., Lima, L. A. S., Garbiate, M. V., Stefanelo, M. S., Müller, M. A., Martins, M. C., Tormen, N. R., Konageski, T. F. (2022). Eficiência de fungicidas para o controle das doenças de final de ciclo da soja, na safra 2021/2022: Resultados sumarizados dos ensaios cooperativos. *Circular técnica*, 183.
- Godoy, C. V., Utiamada, C. M., Meyer, M. C., Campos, H. D., Lopes, I. O. N., Farias, A., Carvalho, A. G., Dias, A. R., Konageski, F. T., Santos, J., Grigolli, F. J., Roy, J. M. T., Belufi, L. M. R., Silva, L. H. C. P., Fantin, L. H., Goussain Júnior, M. M., Senger, M., Stefanelo, M. S., Debortoli, M. P., Martins, M. C., Tormen, N. R., Konageski, T. F. (2023). Eficiência de fungicidas para o controle das doenças de final de ciclo da soja, na safra 2022/2023: Resultados sumarizados dos ensaios cooperativos. *Circular técnica*, 193.
- Godoy, C. V., Utiamada, C. M., Meyer, M. C., Campos, H. D., Lopes, I. O. N., Tomen, A., Dias, A. R.; Sichoeki, D., Konageski, F. T., Araújo Júnior, I. P., Bonani, J. C., Nunes Junior, J., Sato, L. N., Lima, L. A. S., Garbiate, M. V., Stefanelo, M. S.,

- Müller, M. A., Martins, M. C., Konageski, T. F., Carlin, V. J. (2021). Eficiência de fungicidas para o controle das doenças de final de ciclo da soja, na safra 2020/2021: resultados sumarizados dos ensaios cooperativos. Circular técnica, 176.
- Godoy, C., Utiamada, C., Meyer, M., Campos, H., Lopes, I., Tomen, A., Mochko, A. C. R., Dias, A. R., Forcelini, C. A., Siqueri, F. V., Santos, J., Galdino, J. V., Ascari, J. P., Araújo Júnior, I. P., Belufi, L. M. R., Silva, L. H. C. P., Sato, L. N., Goussain Júnior, M. M., Senger, M., Stefanelo, M. S., Müller, M. A., Debortoli, M. P., Tormen, N. R., Roehrig, R. (2024). Eficiência de fungicidas para o controle das doenças de final de ciclo da soja, na safra 2023/2024: Resultados sumarizados dos ensaios cooperativos.
- Gomes, M. R. (2023). Evolução e Perspectivas De Desempenho Econômico e Produção Da Soja Nos Contextos Brasileiro e Paranaense. Revista (RE) DEFINIÇÕES DAS FRONTEIRAS, 1(2), 349-360.
- Han, Y.S. (1959) Studies on purple spot of soybean. Journal of Agriculture and Forestry, 8, 1–32.
- Hartman, G. L., Bowen, C. R., Haudenschild, J. S., Fox, C. M., Cary, T. R., Diers, B. W., (2015b). Evaluation of disease and pest damage on soybean cultivars released from 1923 through 2008 under field conditions in central Illinois. Agronomy Journal 107, 2373-2380.
- Hartman, G. L., Rupe, J. C., Sikora, E. J., Domier, L. L., Davis, J. A., Steffey, K. L. (Eds.). (2015a). Compendium of soybean diseases and pests. St. Paul, MN: American Phytopathological Society.
- Henning, A. A., França Neto, J. B., Henning, F. A., Krzyzanowski, F. C., Lorini, I. (2019). Ocorrência de mancha púrpura (*Cercospora kikuchii*) em sementes de soja no Brasil e seu efeito na qualidade fisiológica: mito ou verdade?. Comissão de Tecnologia de Sementes, 227-229.
- Higgins, J., Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. Stat. Med. 21:1539-1558.
- Hock, J., Kranz, J., Renfro, B. L. (1992). Tests of standard diagrams for field use in assessing the tarspot disease complex of maize (*Zea mays*). International Journal of Pest Management, 38(3), 314-318.
- Imazaki, I., Iizumi, H., Ishikawa, K., Sasahara, M., Yasuda, N., Koizumi, S. (2006) Effects of thiophanate-methyl and azoxystrobin on the composition of *Cercospora kikuchii* populations with thiophanate-methyl-resistant strains. Journal of General Plant Pathology, 72, 292–300.
- Imazaki, I., Sasahara, M., Koizumi, S. (2007) Spatial distribution of purple seed stain of soybean caused by *Cercospora kikuchii* in fields. Journal of General Plant Pathology, 73, 41–45.
- Kandel, Y. R., Bradley, C. A., Chilvers, M. I., Mathew, F. M., Tenuta, A. U., Smith, D. L., Wise, K. A., Mueller, D. S. (2020). Relationship between sudden death syndrome caused by *Fusarium virguliforme* and soybean yield: a meta-analysis.

- Plant disease, 104(6), 1736-1743.
- Kikuchi, R. (1924) The scientific researches of the alumni association of Utsunomiya Agricultural College (Japan) Vol. I. 7–25.
- Kudo, A. S., Blum, L. E. B., Lima, M. A. (2011) Aerobiology of *Cercospora kikuchii*. *Ciência Rural*, 41, 1682–1688.
- Lee, J. H., Hwang, S. R., Lee, Y. H., Kim, K., Cho, K. M., Lee, Y. B. (2015). Changes occurring in compositions and antioxidant properties of healthy soybean seeds [*Glycine max* (L.) Merr.] and soybean seeds diseased by *Phomopsis longicolla* and *Cercospora kikuchii* fungal pathogens. *Food Chemistry*, 185, 205–211.
- Lehner, M. S., Pethybridge, S. J., Meyer, M. C., Del Ponte, E. M. (2017). Meta-analytic modelling of the incidence–yield and incidence–sclerotial production relationships in soybean white mould epidemics. *Plant Pathology*, 66(3), 460-468.
- Lim, S. M. (1979). Evaluation of soybean for resistance to *Septoria* brown spot. *Plant Dis Rep.* 63:242–245.
- Lim, S. M. (1980). Brown spot severity and yield reduction in soybean. *Phytopathology*, 70(10), 974-977.
- Lin, H. A., Villamil, M. B., Mideros, S. X. (2021). Characterization of *Septoria* brown spot disease development and yield effects on soybean in Illinois. *Canadian Journal of Plant Pathology*, 43(1), 62-72.
- Madden, L. V., Hughes, G., Van Den Bosch, F. (2007). The study of plant disease epidemics.
- Madden, L. V., Paul, P. A. (2009). Assessing heterogeneity in the relationship between wheat yield and *Fusarium* head blight intensity using random-coefficient mixed models. *Phytopathology*, 99(7), 850-860.
- Madden, L. V., Paul, P. A. (2011). Meta-analysis for evidence synthesis in plant pathology: An overview. *Phytopathology*, 101(1), 16-30.
- Madden, L. V., Piepho, H. P., Paul, P. A. (2016). Statistical models and methods for network meta-analysis. *Phytopathology*, 106(8), 792-806.
- Martins, M. C. (1998). Desempenho produtivo dos cultivares de soja IAC-17, IAC-12 e IAC-19, semeados em três épocas de semeadura e em cinco densidades de plantas. [Master's Thesis]. Piracicaba: Universidade de São Paulo.
- Martins, M. C., Guerzoni, R. A., Câmara, G. M. D. S., Mattiazzi, P., Lourenço, S. A., Amorim, L. (2004). Escala diagramática para a quantificação do complexo de doenças foliares de final de ciclo em soja. *Fitopatologia Brasileira*, 29, 179-184.
- Meira, D., Woyann, L. G., Bozi, A. H., Milioli, A. S., Beche, E., Panho, M. C., Madella, L. A., Barrionuevo, F., Marchioro, V. S., Benin, G. (2020). Asian soybean rust: a scientometric approach of *Phakopsora pachyrhizi* studies. *Euphytica*, 216, 1-12.
- Mello, F. E., Lopes-Caitar, V. S., Prudente, H., Xavier-Valencio, S. A., Franzenburg, S.,

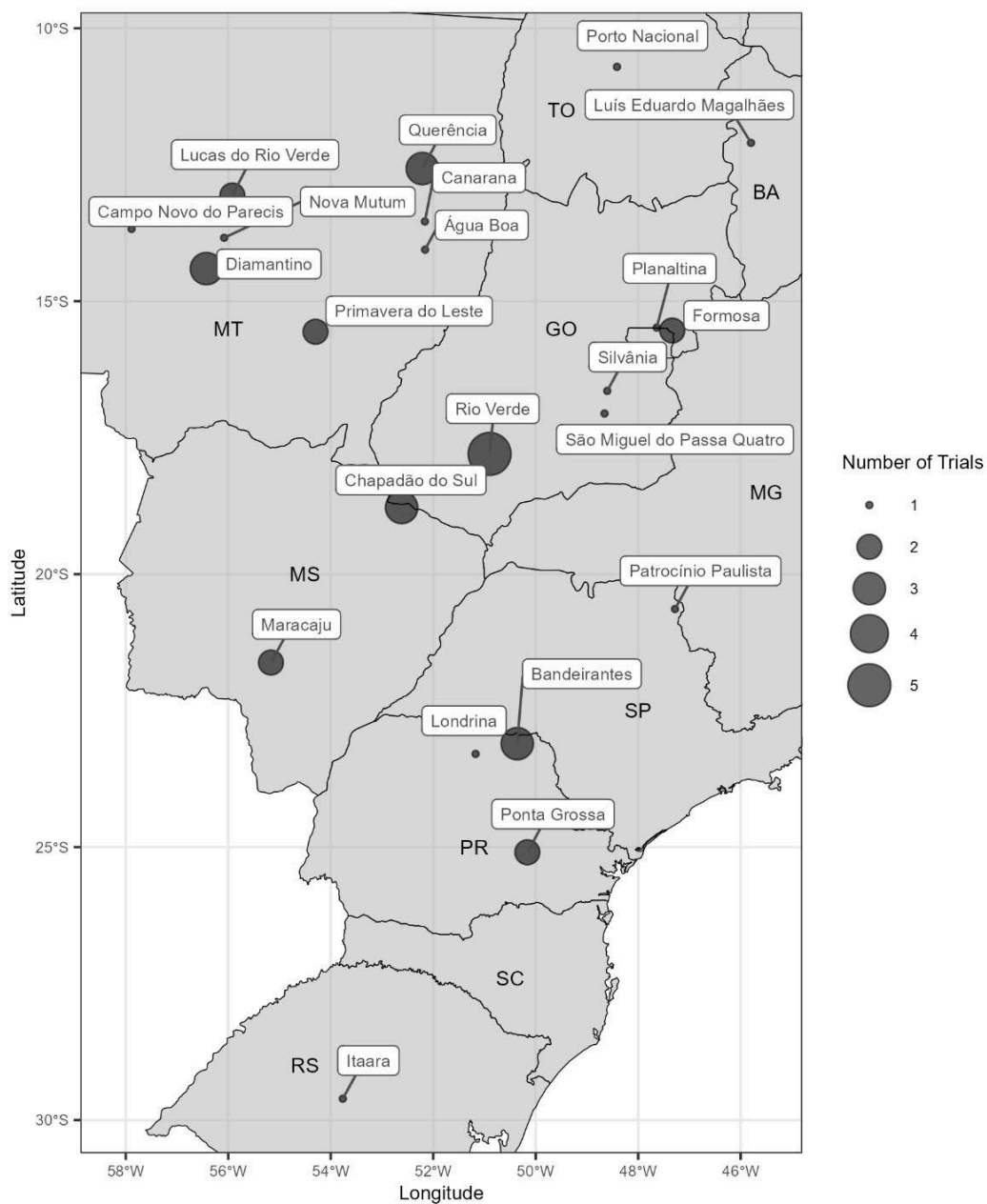
- Mehl, A., Marcelino-Guimaraes, F. C., Verreet, J. A., Balbi-Peña, M. I., Godoy, C. V. (2021). Sensitivity of *Cercospora* spp. from soybean to quinone outside inhibitors and methyl benzimidazole carbamate fungicides in Brazil. *Tropical Plant Pathology*, 46, 69-80.
- Mueller D, Wise K, Sisson A, Smith D, Sikora E, Bradley C, Robertson A. (2016). A farmer's guide to soybean diseases. St. Paul(MN): American Phytopathological Society Press.
- Mumford, J. D. and Norton, G. A. 1984. Economics of decision making in pest management. *524 Annu. Rev. Entomol.* 29:157-174.
- Murakishi, H. H. (1951) Purple seed stain of soybean. *Phytopathology*, 41, 305–318.
- Negrisoli, M. M., Silva, F. N. D., Negrisoli, R. M., Lopes, L. D. S., Souza Júnior, F. D. S., Freitas, B. R. D., Velini, E. D., Raetano, C. G. (2022). Impact of fungicide application timing based on soybean rust prediction model on application technology and disease control. *Agronomy*, 12(9), 2119.
- Pathan, M. A., Sinclair, J. B., McClary, R. D. (1989). Effects of *Cercospora kikuchii* on soybean seed germination and quality. *Plant Disease*, 73, 720–723.
- R Core Team. (2020). RA language and environment for statistical computing, R Foundation for Statistical. Computing.
- Reis, E. M., Hoffmann, L. L., Blum, M. (2002). Modelo de ponto crítico para estimar os danos causados pelo oídio em cevada. *Fitopatologia Brasileira*, 27, p. 644–646.
- Reis, E. M., Reis, A. C., Zanatta, M. (2018). Reflexo econômico e desenvolvimento da resistência de *Phakopsora pachyrhizi* a fungicidas em função do número de aplicações. *Summa Phytopathologica*, 44(3), 289-292.
- Rollins, J. A., Ehrenshaft, M., Upchurch, R. G. (1993). Effects of light- and altered-cercosporin phenotypes on gene expression in *Cercospora kikuchii*. *Canadian Journal of Microbiology*, 39, 118–124.
- Roy, K. W., Abney, T. S. (1976). Purple seed stain of soybeans. *Phytopathology*, 66, 1045–1049.
- Santos, G. B., de Oliveira Coelho, M. A., Del Ponte, E. M. (2023). Critical-point yield loss models based on incidence and severity of wheat head blast epidemics in the Brazilian Cerrado. *European Journal of Plant Pathology*, 165(3), 421-431.
- Sautua, F. (2021). Sensibilidad y resistencia a fungicidas de *Cercospora kikuchii*, agente causal del tizón de la hoja y mancha púrpura de la semilla de la soja. [PhD thesis]. La Plata, Buenos Aires, Argentina: Universidad Nacional de La Plata.
- Sautua, F. J., Pizá, M. C. P., Scandiani, M. M., Carmona, M. A. (2024). *Cercospora* leaf blight and purple seed stain of soybean: A permanent challenge. *Plant Pathology*, 00:1-24.
- Sautua, F. J., Searight, J., Doyle, V. P., Scandiani, M. M., Carmona, M. A. (2020). *Cercospora* cf. *nicotianae* is a causal agent of *Cercospora* leaf blight of

- soybean. *European journal of plant pathology*, 156, 1227-1231.
- Savary, S., Teng, P. S., Willocquet, L., Nutter Jr, F. W. (2006). Quantification and modeling of crop losses: a review of purposes. *Annu. Rev. Phytopathol.*, 44(1), 89-112.
- Schuh, W. (1991). Influence of temperature and leaf wetness period on conidial germination in vitro and infection of *Cercospora kikuchii* on soybean. *Phytopathology*, 81, 1315–1318.
- Schuh, W. (1992). Effect of pod developing stage, temperature, and pod wetness duration on the influence of purple seed stain of soybean. *Phytopathology*, 82, 446–451.
- Schuh, W. (1993). Influence of interrupted dew periods, relative humidity, and light on disease severity and latent infections caused by *Cercospora kikuchii* on soybean. *Phytopathology*, 83, 109–113.
- Schuh, W., Adamowicz, A. (1993). Influence of assessment time and modeling approach on the relationship between temperature-leaf wetness periods and disease parameters of *Septoria glycines* on soybeans. *Phytopathology*, 83(9), 941-948.
- Seixas, C. D. S., Soares, R. M., Godoy, C. V., Meyer, M. C., Costamilan, L. M., Dias, W. P., Almeida, A. (2020). Manejo de doenças. In: Seixas, C. D. S., Neumaier, N., Balbinot Junior, A. A., Krzyzanowski, F. C., Leite, R. M. V. B. C. (Ed). *Tecnologias de produção de soja*. Londrina: Embrapa Soja, 2020. p. 227-264. (Embrapa Soja. Sistema de Produção, 17).
- 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.
- Sherwood, R. T., Berg, C. C., Hoover, M. R., Zeiders, K. E. (1983). Illusions in visual assessment of *Stagonospora* leaf spot of orchardgrass. *Phytopathology*, 73(2), 173-177.
- Sinclair, J. B. (1991). Latent infection of soybean plants and seeds by fungi. *Plant Disease*, v. 75, p.220-224.
- Soares, A. P. G., Guillin, E. A., Borges, L. L., Silva, A. C. D., Almeida, Á. M. D., Grijalba, P. E., Gottlieb, A. M., Bluhm, B. H., Oliveira, L. O. D. (2015). More *Cercospora* species infect soybeans across the Americas than meets the eye. *PLoS One*, 10(8):e0133495.
- Suzuki, K. (1921) Studies on the cause of “Shihan” of soybean. *Chosen Nokaiho*, 16, 24–28.
- Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of statistical software*, 36(3), 1-48.
- Voorra, V., Bermúdez, S., Le, H., Larrea, C., Luna, E. (2024). *Global Market Report: Soybean prices and sustainability*.
- Walters, H. J. (1978). *Cercospora* leaf blight of soybeans. *Phytopathology News*

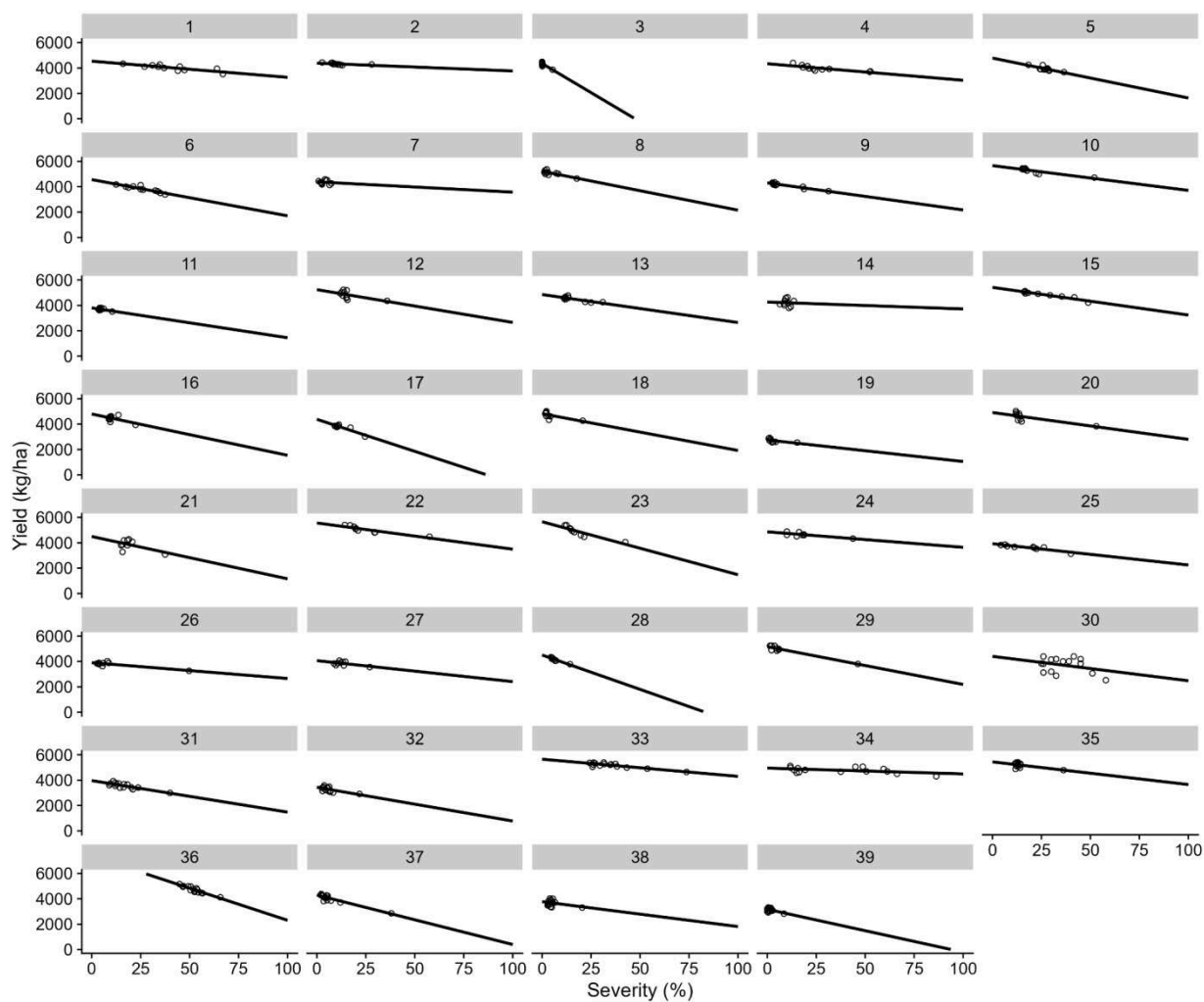
12:165-166.

- Walters, H.J. (1980) Soybean leaf blight caused by *Cercospora kikuchii*. *Plant Disease*, 64, 961–962.
- Ward, N. A., Schneider, R. W., Chanda, A., Silva, E. C., Price, P. P., Cai, G. (2015) *Cercospora* leaf blight and purple seed stain. In: Hartman, G. L., Rupe, J. C., Sikora, E. J., Domier, L. L., Davis, J. A., Steffey, K. L. (Eds.) *Compendium of soybean diseases and pests*, 5th edition. St Paul, MN: APS Press, pp. 37–41.
- Wolf, F. A. (1923). Report of the division of plant pathology. N Carolina Argi. Exp. Stn. Annual Report 46:92.
- Wrather, J. A., Anderson, T. R., Arsyad, D. M., Gai, J., Ploper, L. D., Porta-Puglia, A., Ram, H. H., Yorinori, J. T. (1997). Soybean disease loss estimates for the top 10 soybean producing countries in 1994. *Plant Disease*, 81, 107–110.
- Yeh, C. C., Sinclair, J. B. (1979). Conidium ontogeny and morphology of *Cercospora kikuchii*. *Mycotaxon*, 10, 93–98.
- Zanon, A. J., Streck, N. A., Richter, G. L., Becker, C. C., Rocha, T. S. M. D., Cera, J. C., Winck, J. E. M., Cardoso, Â. P.; Tagliapietra, E. L., Weber, P. S. (2015). Contribuição das ramificações e a evolução do índice de área foliar em cultivares modernas de soja. *Bragantia*, 74, 279-290.
- Zivanovic, M., Ward, B., Price, P. P., Chen, Z. Y. (2021). Elucidation of factors contributing to onset of *Cercospora* leaf blight during later reproductive development of soybean. *Plant Pathology*, 70(9), 2074-2085.

## 7 SUPPLEMENTARY



**Figure S1.** Municipalities where the 39 trials were conducted to compare the efficacy of fungicides in controlling late season diseases in soybean and the data will be used in this study.



**Figure S2.** Relationship between late season diseases severity (%) and soybean yield (kg/ha) for 39 different experimental trials used in this study.