agronomy

Article

Management Efficacy and Response to Post-Application Precipitation of Fungicides for Southern Stem Rot of Peanut and Evaluation of Co-Application with Micronized Sulfur

Daniel J. Anco [1,*], Justin Hiers [1] and Brendan Zurweller [2]

[1] Edisto Research and Education Center, Plant and Environmental Sciences, Clemson University, Blackville, SC 29817, USA
[2] Department of Plant and Soil Sciences, Mississippi State University, Mississippi State, MS 39762, USA; brendan.zurweller@msstate.edu
* Correspondence: danco@clemson.edu

Abstract: Southern stem rot (SSR) is caused by *Athelia rolfsii* and is an economically important disease of peanut (*Arachis hypogaea* L.). Application of protectant fungicides is an effective management component for reducing levels of this soil-borne disease. The majority of peanut hectarage in South Carolina and Mississippi is rainfed. Timely precipitation has the potential to aid the movement of foliar-applied fungicides through the canopy and into contact with soil interfaces where SSR infections occur. Questions have arisen as to the quantitative relationship of post-application precipitation and fungicide-active ingredient efficacy in managing SSR and protecting associated pod yield potentials. To examine this, fungicide efficacy experiments were screened for inclusion in a meta-analysis, from which eleven experiments conducted from 2015 to 2023 were selected and paired with environmental data from nearby weather stations. Precipitation during the two days following fungicide application was associated with significant reduction in SSR incidence (logit rate of −0.0039/mm) and increased pod yield (log slope of 0.0028/mm). Active ingredient interactions with precipitation among pod yield but not SSR incidence data were present for benzovindiflupyr plus azoxystrobin, flutolanil, and tebuconazole. Fungicides with the greatest levels of control per application at maximum label rates were inpyrfluxam (18.8%), benzovindiflupyr plus azoxystrobin (15.4%), flutolanil (12.3%), and prothioconazole plus tebuconazole (10.5%). Micronized sulfur neither contributed to SSR control nor pod yield increase. Tebuconazole was associated with the greatest % SSR control per fungicide product cost (0.47%/$/ha/application) but was also the treatment with the least amount of control (3.5%) at its maximum label rate. Maximum label rates of benzovindiflupyr plus azoxystrobin (USD 637) and inpyrfluxam (USD 548) were estimated as conferring the greatest returns over the chlorothalonil-only control. Results serve as a helpful reference for farmers and practitioners in selecting fungicide management options and targeting application times, as feasible, to utilize natural precipitation to improve management outcomes.

Keywords: *Athelia rolfsii*; broadcast; groundnut; profitability; *Sclerotium rolfsii*; southern blight; white mold

check for updates

Citation: Anco, D.J.; Hiers, J.; Zurweller, B. Management Efficacy and Response to Post-Application Precipitation of Fungicides for Southern Stem Rot of Peanut and Evaluation of Co-Application with Micronized Sulfur. *Agronomy* **2024**, *14*, 893. https://doi.org/10.3390/agronomy14050893

Academic Editor: Loukas Kanetis

Received: 30 March 2024
Revised: 22 April 2024
Accepted: 24 April 2024
Published: 25 April 2024

1. Introduction

Southern stem rot (SSR), caused by *Athelia rolfsii* (Curzi) C.C Tu and Kimbr (syn. *Sclerotium rolfsii* Sacc.), is an economically important disease of peanut found in practically all areas of the world where peanut is commercially grown [1–3]. Symptoms of SSR include chlorosis and necrosis of laterals and foliage, light to dark brown lesions on pegs and portions of branches in contact with soil, and rotted pods [1–3]. Infections of SSR are often accompanied by white mycelia and white, tan, or dark brown sclerotia near the soil line [2]. Yield loss due to this disease is generally <25%, but has been reported to range from less than 10% to near 40% [2–5]. Plant species capable of serving as a host for *A. rolfsii* infection exceed 200 to 500 spp. [2,6]. Current recommendations for management of SSR include the integration of factors such as crop rotation to non-hosts, planting cultivars with resistance where available, planting during field and environmental conditions favorable to rapid plant growth, and the timely application of effective preventative fungicides [2,3,7]. Previous research has reported that fungicide application efficacy could be improved by spraying active ingredients at night when peanut tetrafoliate leaves are folded [8,9]. While effective on a mechanistic level in aiding fungicide penetration through the canopy and subsequent deposition proximal to SSR infection sites at the plant–soil interface, spraying during the night poses a logistical burden on the applicator and displaces time typically allocated for sleeping.

While irrigation, where available, can analogously be used to facilitate fungicide movement through the canopy [3,7,10], peanut production in South Carolina (SC) and Mississippi (MS) is predominantly rainfed (~80% planted hectares). As opportunities allow, timing fungicide applications to precede rain can similarly improve their efficacy in managing soil-borne diseases [7], although whole-farm operation logistics and rainfall variability limit the practical capacity for every application to capitalize upon rain-assisted movement through the canopy. Whereas general effects of irrigation or precipitation on SSR development have been variable across individual years and locations [11–13], the contribution of irrigation to SSR management on inoculated pods has been reported to decrease as the length of time until irrigation increased [10]. Not surprisingly, an inverse relationship was reported between irrigation timing and leaf spot management [10], whereas pod yield was not examined. These studies provide helpful context, but questions continue to be raised regarding the relationships between precipitation under dryland production environments, SSR management efficacy of further active ingredients, and the preservation of pod yield.

Inpyrfluxam is a recently registered active ingredient that has been labeled for use in managing SSR of peanut as of 2020 [14]. Available data is limited comparing the efficacy of inpyrfluxam to other available fungicide active ingredients. With regard to managing late leaf spot on peanut caused by *Nothopassalora personata*, Culbreath et al. [15] reported a synergistic effect of demethylation inhibitor (DMI) or quinone outside inhibitor (QoI) fungicides co-applied with micronized sulfur [16]. However, published reports on the potential efficacy of micronized sulfur co-application with fungicide active ingredients for management of SSR are lacking. The objectives of this work were to compare efficacy of several fungicide active ingredients across field experiments conducted in SC and MS, quantify influence of temporally proximal rainfall on efficacy of applications, and assess co-application of fungicides with micronized sulfur on SSR management and subsequent pod yield.

2. Materials and Methods

2.1. Dataset

Fungicide efficacy experiments conducted from 2015 to 2023 were examined for meeting criteria for inclusion in a meta-analysis. To be selected for inclusion, experiments needed to report fungicide application dates and rates, include a minimum of two fungicide programs per experiment, report SSR incidence and pod yield data, exhibit average SSR incidence $\geq$ 10% among plots not treated with fungicides active against SSR (e.g., chlorothalonil-only), and be reasonably free from confounding factors (e.g., excessive insect feeding and non-target diseases). Morphological identification of *A. rolfsii* and SSR symptoms [1–3] was considered adequate without requiring molecular confirmation. Active ingredients represented in less than three experiments were excluded from the analysis to buffer against potentially erroneous results arising from reduced treatment population across data. Following screening, a total of eleven experiments were selected. Experiments were conducted at the Edisto Research and Education Center of Clemson University at Blackville, SC (n = 9) or at the Delta Research and Extension Center of Mississippi State University at Stoneville, MS (n = 2). Soil type was a Barnwell loamy sand (fine loamy, kaolinitic, thermic Typic Kanhapludults) in Blackville, SC, and a Bosket very fine sandy loam (fine loamy, mixed, active, thermic Mollic Hapludalfs) in Stoneville, MS. The preceding crop for all but two experiments was peanut, in which case the preceding crop was cotton. Management practices other than fungicide application and crop rotation were based on Extension recommendations [7]. Irrigation was not applied to screened experiments within the ten days following fungicide application. Cultivars within experiments included 'Emery' (n = 1), 'FloRun 107' (n = 1), 'Georgia-06G' (n = 10), 'Georgia-13M' (n = 1), 'Sugg' (n = 1), 'TUFRunner 727' (n = 1), 'Sullivan' (n = 1), and 'Wynne' (n = 1). Experimental design was a randomized complete block with at least four replications. Plot size slightly varied among experiments, but was typically 3.8 × 12.2 m. Represented active ingredients from selected experiments are listed in Table 1.

Table 1. Active ingredient representation across experiments conducted from 2015 to 2023.

Active Ingredient	Rate (kg ai/ha)	Experiments	Treatments	Treatment-Experiments
Chlorothalonil-only	1.26	10	1	10
Benzovindiflupyr plus azoxystrobin	0.08 to 0.1 plus 0.15 to 0.2	9	8	12
Flutolanil	0.53 to 1.07	9	17	27
Inpyrfluxam	0.05 to 0.1	7	20	24
Micronized sulfur [1]	4.48	5	9	12
Tebuconazole	0.2 to 0.23	10	17	22
Prothioconazole	0.11 to 0.2	5	8	8

[1] When present, micronized sulfur was always co-applied with another active ingredient.

Daily precipitation (mm) data were collected from nearby weather stations ($\leq$3 km from experiment sites) at the Edisto Research and Education Center and the Delta Research and Extension Center. Precipitation totals from one to seven days following fungicide application were examined for use in modeling and subsequently reduced to one or two days following fungicide application by way of Akaike's Information Criterion (AIC) minimization. Precipitation occurring on the day of fungicide application was excluded from final analysis due to the lack of improvement of model fits and the inability of the resolution of daily weather data to distinguish between rainfall occurring before or after fungicides were applied. Variable (dynamic) weighting of the contribution of rainfall from the first versus the second day following fungicide application was examined but not further described due to the lack of improvement of model fits. To explore a potential time-of-season-dependent (i.e., as a proxy for increasing canopy size, which was not measured) contribution of precipitation in affecting SSR incidence management or pod yield production, evaluation of precipitation effects was conducted over the total range of application dates and selected subsets thereof (e.g., $\geq$75 days after planting [DAP]) (Figures 1 and 2).

2.2. Data Analysis

Analysis of the raw data was conducted according to a one-stage meta-analysis [17–19]. Data were analyzed according to Equation (1):

$$\mathrm{Y}_{rnxv} = (\mathrm{B}_{rn} + \mathrm{F}_{rn} + \mathrm{I}_{rn} + \mathrm{P}_{rn} + \mathrm{T}_{rn} + \mathrm{M}_{rn} + \mathrm{Intercept}) \times (1 + \mathrm{dd\_mm}_{n}) + \mathrm{C}_{r} + Cv_{v}E_{x} + V_{rnxv}, \quad (1)$$

where Y was the response (proportion SSR incidence or pod yield (kg/ha)) of cultivar v within experiment x treated with fungicide active ingredients applied at rate r and n no. of applications, B_{rn} = benzovindiflupyr plus azoxystrobin application rate $r \times n$ no. of applications, F_{rn} = flutolanil application rate $r \times n$ no. of applications, I_{rn} = inpyrfluxam application rate $r \times n$ no. of applications, P_{rn} = prothioconazole application rate $r \times n$ no. of applications, T_{rn} = tebuconazole application rate $r \times n$ no. of applications, M_{rn} = micronized sulfur application rate $r \times n$ no. of applications, $\mathrm{dd\_mm}_{n}$ is mm of accumulated precipitation during the one or two subsequent days following respective n fungicide active ingredient applications (interaction term) or total accumulated precipitation during the one or two subsequent days following all fungicide applications in a given treatment experiment (represented as $\text{dd\_mm}_n \times$ Intercept, which allowed estimation of its simple-effect slope), C_r = chlorothalonil application rate r (simplified from C_{rn} due to the latter term's lack of improved fit), Cv_vE_x is the random effect of cultivar v within experiment x, and V_{rnxv} is the residual variance with dispersion parameter (φ) corresponding to the distribution of the response variable. Incidence of SSR was modeled according to a beta distribution ($V = \mu(1 - \mu)/(\varphi + 1)$) with a logit link, and pod yield was modeled according to a Tweedie distribution ($V = \varphi\mu^{Power}$ where *Power* was 1) with a log link. Model fitting was conducted within the glmmTMB procedure [20] in R 4.2.3 [21] using maximum likelihood. Selection of the best fitting models was determined according to AIC minimization. Reliability of Equation (1) in predicting observed values was assessed with the concordance correlation coefficient (CCC) [22]. Estimated confidence intervals were calculated from parameter likelihood profiles at the 95% level.

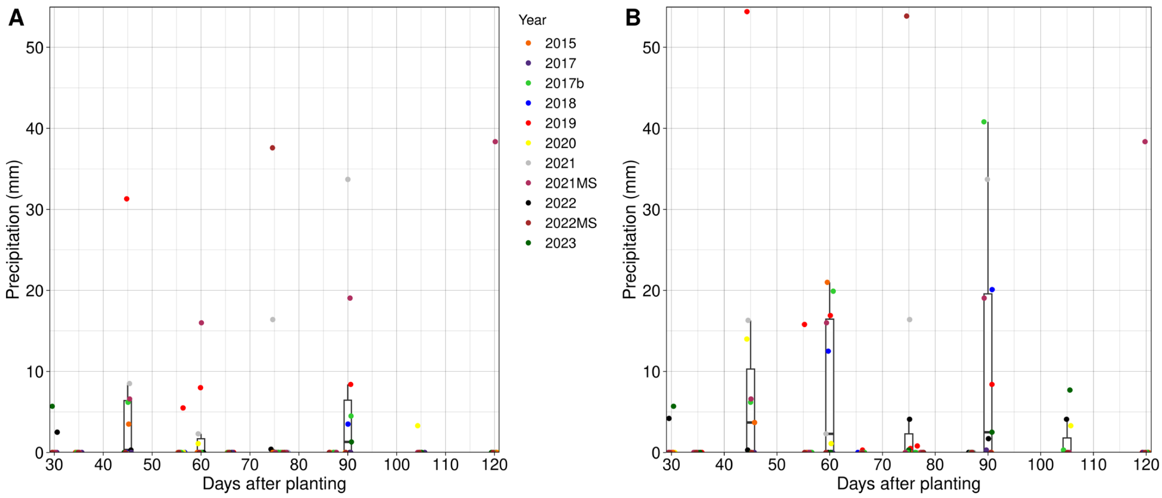

Figure 1. Boxplots of total precipitation from the (**A**) one or (**B**) two days following individual fungicide applications at different timings from experiments conducted from 2015 to 2023.

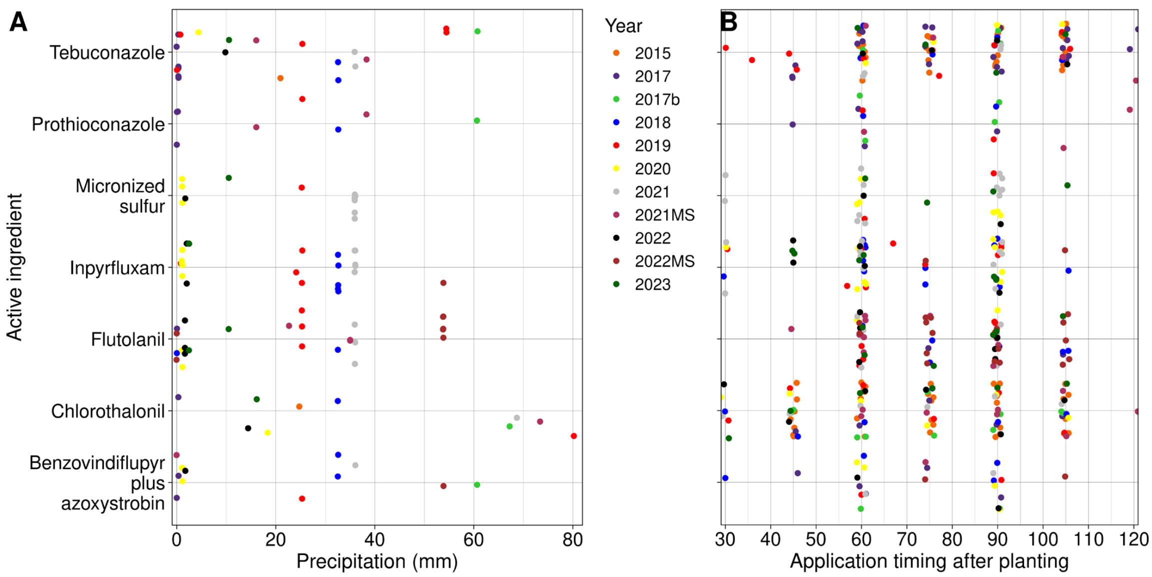

Figure 2. (**A**) Total precipitation from the two days following fungicide active ingredient applications across all application timings and (**B**) application timing of fungicide active ingredients within experiments conducted from 2015 to 2023.

3. Results and Discussion

3.1. Southern Stem Rot

Incidence of SSR varied among treatment experiments, ranging from 0.7% to 92.4%. The majority (69%) of treatment-experiments exhibited <20% incidence (Figure 3A). Mean pod SSR incidence among chlorothalonil-only treated plots was 38%. This was approximately 30% less than that reported by Woodward et al. [10] for manually inoculated pods from microplots treated with chlorothalonil only (~68%). The best fitting model describing the relationship of SSR incidence among fungicide treatments included precipitation over the two days following fungicide application as an independent variable and excluded its interaction with fungicide active ingredients (Table 2, Figure 4A). Reliability of the model in predicting observed SSR incidence was 88.2%, which was similar to that of competing models. The fit of the model to the data was not improved when precipitation amounts under consideration were restricted to latter portions of the growing season (only after 60, 75, or 90 DAP) compared to the total range of fungicide application timings (Table 3). While canopy sizes were not explicitly measured in these experiments, this result supports the effect of precipitation in contributing to SSR management having been consistent over the course of the examined growing seasons, within which canopy size increased as the peanut crop grew. Previous research reported a lack of contribution of precipitation to the presence of *A. rolfsii* hyphal [13], which supports the estimated (negative) effect of precipitation in the current work as being related to overall fungicide efficacy (i.e., improved control) rather than affecting disease progression through inhibiting growth of the fungus itself. Supporting this, total precipitation from the day of (any) fungicide application through to seven days following application did not affect SSR incidence (p = 0.978). In contrast, Bowen [12] reported higher SSR incidence in irrigated compared to rainfed plots in experiments from two out of three years, and Davis [11] reported greater SSR incidence in one of two years. Both studies reported a tendency toward non-significant differences between irrigated and rainfed plots when soil moisture during the year was more frequently at saturated levels. Saturated soil conditions were not predominant among screened experiments in the present work.

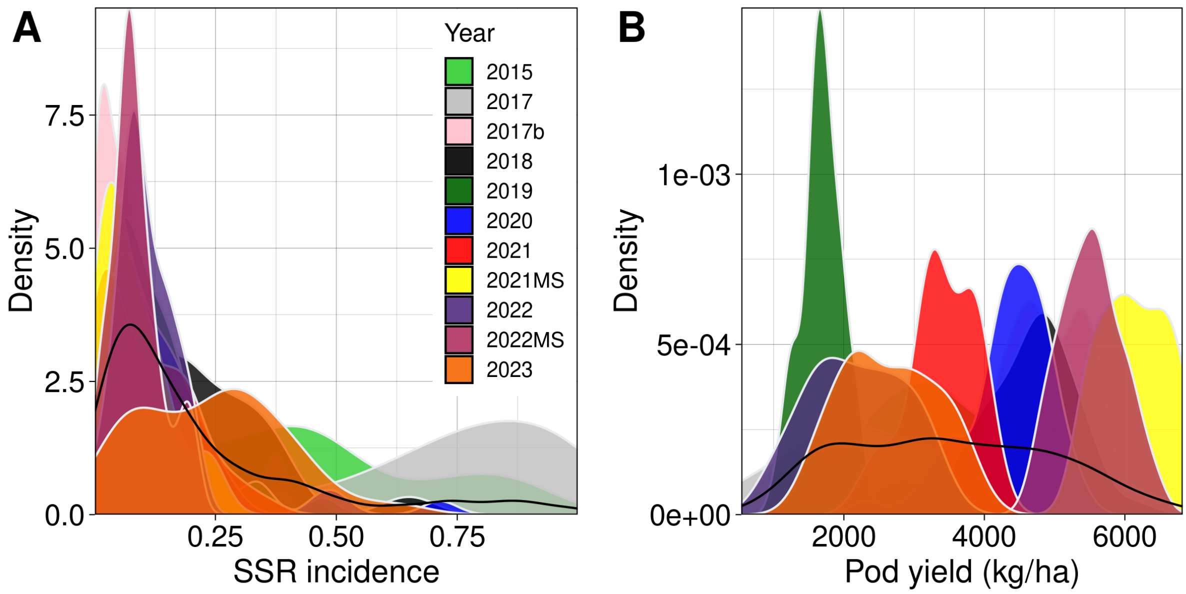

Figure 3. Distribution of (**A**) southern stem rot (SSR) incidence and (**B**) pod yield from experiments conducted from 2015 to 2023. The black line represents the overall distribution across years.

Table 2. Comparison of southern stem rot (SSR) incidence and pod yield (kg/ha) models' performance for precipitation accumulated over one or two days subsequent to fungicide application, with regard to all fungicide application dates.

Response	Subsequent Days Considered	$dd\_mm_n \times$ a.i. [1]	φ [2]	AIC [3]	CCC [4]
SSR incidence	One	Yes	12.1	−833.8	0.885
	Two		11.8	−827.5	0.882
	One	No	11.7	−834.7	0.882
	Two		11.7	−837.1	0.882
Pod yield	One	Yes	88.4	6505.9	0.897
	Two		88.4	6493.9	0.900
	One	No	96.3	6517.0	0.893
	Two		96.3	6513.0	0.894

[1] $dd\_mm_n \times$ a.i. = inclusion of precipitation × active ingredient interaction terms in the model. [2] Dispersion parameter of the beta (SSR incidence) or Tweedie (pod yield) distribution. [3] AIC = Akaike's Information Criterion. [4] CCC = Concordance correlation coefficient.

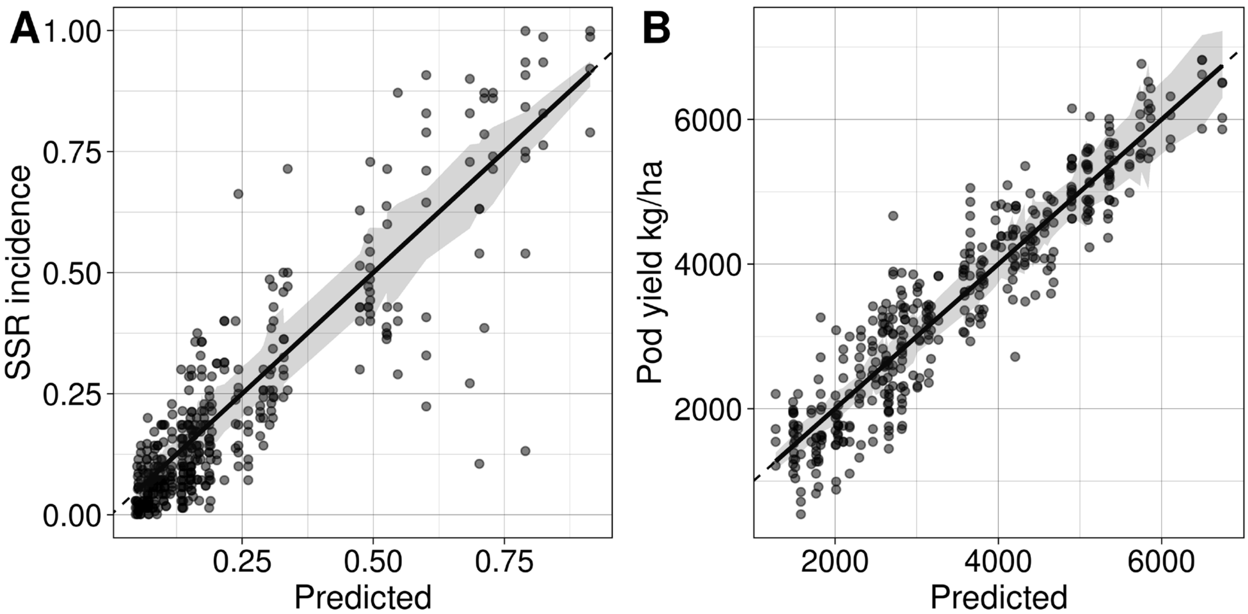

Figure 4. Observed versus predicted (**A**) southern stem rot (SSR) incidence and (**B**) pod yield from experiments conducted from 2015 to 2023. Shaded ribbons are 95% confidence intervals. Model reliability was calculated according to the concordance correlation coefficient and estimated to be 0.882 (SSR incidence) and 0.900 (pod yield). Dashed lines are lines of perfect agreement.

Table 3. Comparison of southern stem rot (SSR) incidence and pod yield (kg/ha) models' performance for precipitation accumulated over two days subsequent to fungicide application for varying fungicide application periods.

Response	Precipitation Period Considered	$dd\_mm_n \times$ a.i. [1]	φ [2]	AIC [3]	CCC [4]
SSR incidence	All	No	11.7	−837.1	0.882
	≥60 days after planting		11.7	−838.8	0.882
	≥75 days after planting		11.7	−838.9	0.882
	≥90 days after planting		11.7	−837.1	0.881
Pod yield	All	Yes	88.4	6493.9	0.900
	≥60 days after planting		88.4	6500.0	0.899
	≥75 days after planting		88.4	6499.3	0.899
	≥90 days after planting		88.4	6497.9	0.900

[1] $dd\_mm_n \times$ a.i. = inclusion of precipitation × active ingredient interaction terms in the model (i.e., selection based on model comparisons). [2] Dispersion parameter of the beta (SSR incidence) or Tweedie (pod yield) distribution. [3] AIC = Akaike's Information Criterion. [4] CCC = Concordance correlation coefficient.

Estimated slopes of the response of (logit) SSR incidence for single applications of fungicide active ingredients are listed in Table 4. With the exception of chlorothalonil and micronized sulfur ($p > 0.25$), all fungicide active ingredient slopes were significant ($p < 0.035$). Micronized sulfur has previously been reported to improve the efficacy of DMI or QoI fungicide-active ingredients for management of late leaf spot (*Nothopassalora personata*) in peanut [15,16]. This is, to our knowledge, the first report documenting the lack of a contribution of micronized sulfur in managing SSR in field experiments. The active ingredient with the greatest per unit (kg/ha) decrease in SSR logit incidence was inpyrfluxam (−7.95) followed by benzovindiflupyr plus azoxystrobin (−6.75) (Table 5). Maximum label rate applications of corresponding fungicides (Excalia and Elatus, respectively) translate to 18.8% SSR control (95% CI: 14.2 to 23.0%) for inpyrfluxam and 15.4% SSR control (95% CI: 11.3 to 19.4%) for benzovindiflupyr plus azoxystrobin. Application of flutolanil (Convoy) at the maximum label rate was associated with the next greatest level of control at 12.3% (95% CI: 7.1 to 17.3%). Control associated with prothioconazole alone exhibited the largest variability (95% CI: 0.9 to 14.1%), control with which (7.3%) was less than a maximum label rate application of inpyrfluxam. In practice, prothioconazole is typically co-applied with tebuconazole (commercially labeled as Provost Silver). The estimated % SSR control of the maximum label rate of such a mixture was not significantly different from that of the active ingredients exhibiting the greatest levels of SSR control (inpyrfluxam, benzovindiflupyr plus azoxystrobin, and flutolanil) (Figure 5). When compared on a % SSR control per fungicide product cost (USD/ha/application) basis, the active ingredient with the greatest control efficiency was tebuconazole (0.47%/USD/ha/application, Table 5). Control efficiencies for benzovindiflupyr plus azoxystrobin and inpyrfluxam were essentially the same, followed by prothioconazole plus tebuconazole, flutolanil, and prothioconazole alone.

Table 4. Estimated parameters for models predicting southern stem rot (SSR) logit incidence or log pod yield (kg/ha) for experiments conducted from 2015 to 2023.

	SSR Incidence			Pod Yield (kg/ha)		
Parameter [1]	**Estimate**	**95% CI** [2]	***p***	**Estimate**	**95% CI**	***p***
Intercept	−0.5560	−1.2776, 0.1596	0.117	7.9739	7.7444, 8.2023	<0.001
C	0.1847	−0.1325, 0.5030	0.254	−0.2061	−0.2965, −0.1184	<0.001
B	−6.7462	−8.6401, −4.8492	<0.001	1.9218	1.4424, 2.3896	<0.001
F	−0.4723	−0.6765, −0.2698	<0.001	0.0766	0.0319, 0.1204	0.003
I	−7.9504	−10.0211, −5.8846	<0.001	1.4272	0.8490, 2.0110	<0.001
M	−0.1371	−0.3854, 0.0969	0.263	0.0504	−0.0366, 0.1365	0.258
P	−1.4566	−2.8694, −0.1686	0.033	0.0295	−0.3636, 0.4164	0.883
T	−0.6383	−1.0792, −0.1986	0.004	0.2829	0.1599, 0.4087	<0.001
dd_mm	−0.0039	−0.0077, −0.0001	0.042	0.0028	0.0017, 0.0039	<0.001
B × dd_mm	--	--	--	−0.0245	−0.0361, −0.0128	<0.001
F × dd_mm	--	--	--	−0.0014	−0.0014, −0.0014	0.014
I × dd_mm	--	--	--	−0.0099	−0.0241, 0.0042	0.209
M × dd_mm	--	--	--	−0.0017	−0.0052, 0.0018	0.371
P × dd_mm	--	--	--	−0.0072	−0.0165, 0.0024	0.274
T × dd_mm	--	--	--	−0.0067	−0.0105, −0.0028	0.014
Cultivar × Year	0.7414	0.5311, 1.1043	--	0.2700	0.1970, 0.3975	--
φ	11.6978	10.1173, 13.4338	--	88.4159	87.1084, 89.5506	--

[1] Active ingredient parameter estimates and confidence intervals are per unit rate (kg ai/ha, except for micronized sulfur, which was scaled to 10s of kg ai/ha for presentation) per no. of applications. Active ingredient parameters correspond to chlorothalonil, C, benzovindiflupyr plus azoxystrobin, B, flutolanil, F, inpyrfluxam, I, micronized sulfur, M, prothioconazole, P, and tebuconazole, T. Cultivar × Year random effects are estimated standard deviations, and φ is the dispersion parameter specified by the beta distribution (SSR incidence) ($V = \mu(1 - \mu)/(\varphi + 1)$) or Tweedie (pod yield) distribution ($V = \varphi\mu^{Power}$ where *Power* was 1). [2] Confidence intervals generated from parameter likelihood profiles from the fitted model.

Table 5. Estimated per ha cost and return associated with fungicide active ingredient applications for management of southern stem rot (SSR) above a chlorothalonil-only control based on experiments conducted from 2015 to 2023.

Active Ingredient	Rate (ai kg/ha)	Cost (USD/ha/ Application)	SSR Control/USD/ha/ Application	Return (USD/ha) [1]
Chlorothalonil-only	1.26	USD 12.0	−0.48%	USD 0
Benzovindiflupyr plus azoxystrobin	0.07 plus 0.15	USD 46.5	0.26%	USD 574
	0.08 plus 0.17	USD 53.2	0.26%	USD 605
	0.09 plus 0.19	USD 59.8	0.26%	USD 637
Flutolanil	0.53	USD 36.0	0.17%	USD 409
	0.80	USD 54.0	0.17%	USD 425
	1.06	USD 72.0	0.17%	USD 442
Inpyrfluxam	0.05	USD 37.1	0.26%	USD 459
	0.07	USD 55.6	0.26%	USD 502
	0.10	USD 74.1	0.26%	USD 548
Micronized sulfur	4.48	USD 23.5	0.07%	USD 355
Prothioconazole	0.20	USD 67.4	0.11%	USD 320
Tebuconazole	0.22	USD 7.4	0.47%	USD 474
Prothioconazole plus tebuconazole	0.20 plus 0.20	USD 48.9	0.21%	USD 425

[1] Returns were calculated using a peanut contract price set to USD 551/1000 kg (USD 500/ton).

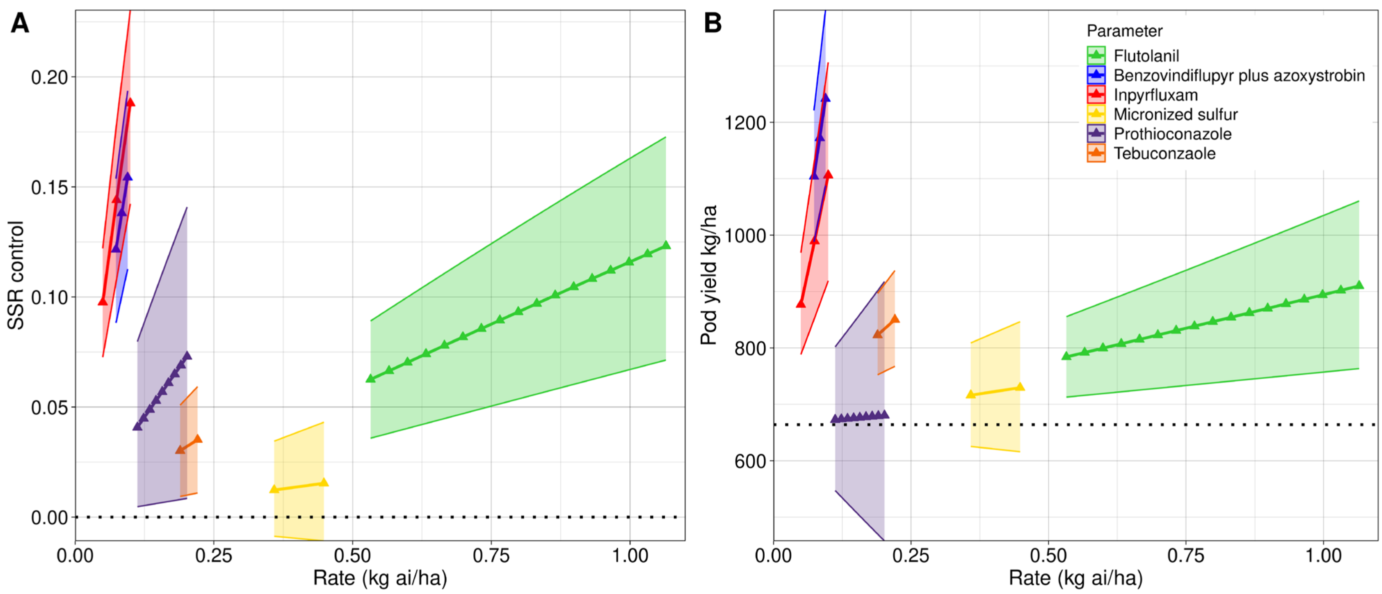

Figure 5. Estimated (**A**) proportion southern stem rot (SSR) control and (**B**) pod yield increase over a chlorothalonil-only control from experiments conducted from 2015 to 2023. Rates are in kg ai/ha for single applications, except for micronized sulfur which was scaled to 10s of kg ai/ha for presentation. Shaded ribbons are 95% confidence intervals. Horizontal dotted reference lines represent (**A**) zero SSR control (i.e., chlorothalonil-only treatment was not different from zero) and (**B**) the intercept from the pod yield model.

Rainfall during the two days following the application of fungicide was estimated to improve SSR control at the rate of 0.1%/mm (logit rate of −0.0039/mm for proportion SSR incidence), which corresponds to 1% per 10 mm rain. The amount reported by Woodward et al. [10] for 10 mm precipitation 48 h after fungicide application was a slightly higher reduction of 2.4% from an upper plateau when rainfall was estimated to no longer contribute to SSR control. When this amount was normalized for the amount of SSR incidence observed in the respective studies' chlorothalonil-only treated plants

(~68% in microplots reported by Woodward et al. [10] compared to ~38% in the present dataset from field experiments), the result (1.4% control per 10 mm precipitation) was similar to that estimated in the present analysis (95% CI: 0 to 1.9% control per 10 mm (0.4″) precipitation). It would be interesting to examine additional datasets from dryland field experiments where a greater abundance and frequency of rainfall within one day following fungicide applications was present. The frequency of fungicide application timings across all application dates (30 to 120 DAP, n = 132 application dates) from screened experiments accompanied by subsequent precipitation was low overall (18.2 and 28.0% of applications were followed by >0.3 mm precipitation in the one or two days following their application, respectively). Frequency of recorded precipitation increased (19.7 and 33.3% for one and two days following application, respectively) when considering the range of application dates when most fungicides were applied (70.8 and 85.7% of all fungicide applications were made between 60 to 90 and 60 to 105 DAP, respectively). Nevertheless, the results from the current study provide helpful context on the effects of rainfall under a slightly wider time window (two days compared to one), which provides greater flexibility for farmers to consider when planning fungicide applications and examining non-omniscient weather forecasts. The amount of SSR control corresponding to 10 to 15 mm (0.4 to 0.6″) rain within two days following fungicide application (1 to 1.5% control) was less than an application of tebuconazole (3.5% control). If field history or environmental conditions [1,7,13] are favorable for the development of SSR, applying efficacious fungicides as close to a rainfall event as possible can help to improve the amount of SSR control available from a given application. Where available, irrigation may likewise be used to facilitate fungicide being washed down from the canopy and into the soil [10]. The distribution of rainfall over an area of space is notoriously variable [23–26]. As such, specific areas of larger fields can receive differing amounts of precipitation from the same rain event. This compounds with the spatially variable nature of *A. rolfsii* [27] to add complexity to the actual amount of benefit an individual field would receive from a fungicide application preceding a given rain. Thus, while weather stations were nearby to experiment sites in the present study, it is possible that actual quantities and timings could have varied compared to those utilized for analysis. Further experimentation could remediate this potential source of error via installation of weather stations immediately adjacent to field sites. Nevertheless, the information as utilized in the present study remains useful for commercial production settings where spatial forecasts of precipitation continue to exhibit variation.

3.2. Pod Yield

Pod yield varied across experiments, ranging from 1000 to 7000 kg/ha (Figure 3B). This range was not unexpected given the different fungicide treatment schedules (Figure 2B) and varying field crop rotations and environmental conditions. Drought conditions occurred in SC in 2019, and it was during that year when overall pod yield levels were lowest (Figure 3B). Nevertheless, the presence of a variety of field conditions was beneficial in the sense that it allowed for the examination of relative pod yield responses over a range of environments. In line with the results from the SSR incidence modeling, mm of precipitation occurring over the two days following fungicide application was included in the best fitting model describing pod yield response (Table 2, Figure 4B). The reliability of this model in predicting observed pod yield was 0.900, which was slightly greater than that of the best fitting model for SSR incidence (0.882). Restriction of fungicide application timings over which precipitation effects were considered did not improve the fit of the model but rather resulted in slightly less descriptive models (Table 3). This is in line with how water is needed for healthy development of peanut throughout the growing season, whereas pod fill in particular is a critical period when peanut is susceptible to water deficit stress [7,28].

In contrast to the results of the SSR incidence model, the best fitting model for pod yield included interaction terms for precipitation and active ingredients (Table 4). Interaction slopes were significant and negative for flutolanil, tebuconazole, and benzovindiflupyr plus azoxystrobin (i.e., lessening precipitation's contribution to pod yield in an active ingredient-dependent manner). Further work would be needed to empirically differentiate between negative interaction slopes mechanistically corresponding to a possible increased fungicide leaching or soil-mobility effect (which could reduce a fungicide's capacity to preserve pod yield quantities through decreased disease management efficacy) or a model-centric yield adjustment (i.e., improving statistical fit of the model to predict varying pod yield data). Results from the SSR modeling (Table 4) were not in support of the first possibility, as slope coefficients corresponding to reduced fungicide efficacy in the presence of increasing precipitation were not present among final candidate models; rather, the precipitation slope estimated from the data indicated an overall increase in management efficacy. In alignment with the SSR incidence model, total precipitation from day-zero through seven days following fungicide application neither affected pod yield levels ($p = 0.251$) nor negated the significance of model precipitation slopes or interactions as reported in Table 4. Rates of pod yield decrease resulting from estimated interaction slopes, while statistically significant, were modest overall. Translating log-scale slope effects to the data scale, pod yield adjustments following 20 mm (0.8″) precipitation in the two days following fungicide application (6% of recorded fungicide applications among screened experiments) were estimated to reduce the pod yield increase estimated from precipitation by ~100 (flutolanil or tebuconazole) to 160 kg/ha (benzovindiflupyr plus azoxystrobin). Pod yield increase due to 20 mm precipitation would otherwise have been estimated at ~170 to 200 kg/ha for a comparable magnitude of pod yield (i.e., in the absence of the precipitation–active ingredient interaction term). Thus, on a practical level, interaction terms for precipitation reduced the estimated contribution precipitation conferred to pod yield production to 42, 84, and 85 kg/ha for benzovindiflupyr plus azoxystrobin, flutolanil, and tebuconazole, respectively.

At intermediate label rates, there was considerable overlap in estimated pod yield increases above a chlorothalonil-only control across fungicide active ingredients (Figure 5B). When considering maximum label rates, the fungicides conferring the greatest pod yield increases (95% CI inclusive of >1100 kg/ha) were benzovindiflupyr plus azoxystrobin (95% CI: 1089 to 1401 kg/ha increase) and inpyrfluxam (95% CI: 920 to 1307 kg/ha increase), followed by flutolanil (95% CI: 764 to 1062 kg/ha increase), prothioconazole plus tebuconazole (95% CI: 761 to 918 kg/ha increase), and tebuconazole (95% CI: 768 to 938 kg/ha increase). Economic return above the chlorothalonil-only control for maximum label rates were estimated to be greatest among benzovindiflupyr plus azoxystrobin, inpyrfluxam, tebuconazole, and flutolanil (USD 637, USD 548, USD 474, and USD 442, respectively) (Table 5). One of the screening criteria used to select experiments for inclusion in the present analysis, which was focused on SSR, was each experiment being reasonably free from confounding factors. This included diseases such as late leaf spot, for which some of the fungicide active ingredients examined in this study contribute management efficacy. As a consequence, while the utilization of this screening factor contributed to a focused dataset in line with the immediate scope at hand, it does not reflect pod yield preservation properties of fungicides that possess efficacy against such diseases (e.g., prothioconazole plus tebuconazole and benzovindiflupyr plus azoxystrobin) [7,14,29]. Interpretation of potential fungicide economic returns as directly translating to future applications should likewise take into account the prevalence and severity of individual diseases, cultivar susceptibilities, field histories, product costs, and environmental conditions in a given crop year. These factors undoubtedly vary and interact to affect the profitability of individual fungicide applications in the presence of final disease levels and pod yield potentials [7,30].

The analytical framework described and utilized in the present work decomposed treatments into no. of applications and rates of active ingredients. This allowed SSR incidence and pod yield responses to be modeled over a range of otherwise diverse treatment combinations that varied both in active ingredient composition and individual application rates. While this likewise facilitated precipitation effects to be examined over a greater total number of application dates and environments under field conditions, this approach is consequently generalizable to other systems where program treatment structure varies across individual experiments. Furthermore, the non-treatment-isolating nature of the present framework allowed for effects to be examined under a variety of treatment application schedules. As a result, this has practical value in the sense that relative effects are more readily translatable to commercial situations where it is not uncommon for fungicide active ingredients to vary across applications, rather than (only) applying individual active ingredients without alternation. Alternation of fungicide-active ingredients is a recommended practice to buffer against possible development or spread of populations resistant to fungicide-active ingredients [7,14,29,31,32]. Results from this work can serve as a helpful reference for farmers and practitioners in selecting fungicide active ingredients and provide context for benefits of rainfall in improving SSR management outcomes.

Author Contributions: Conceptualization, D.J.A.; methodology, D.J.A.; software, D.J.A.; validation, D.J.A.; formal analysis, D.J.A.; investigation, D.J.A.; resources, D.J.A. and B.Z.; data curation, D.J.A.; writing—original draft preparation, D.J.A.; writing—review and editing, D.J.A., J.H. and B.Z.; visualization, D.J.A.; supervision, D.J.A.; project administration, D.J.A.; funding acquisition, D.J.A. All authors have read and agreed to the published version of the manuscript.

Funding: Program support was provided by the South Carolina Peanut Board. This material is based upon work supported by NIFA/USDA, under project number SC-1700592.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: Technical Contribution No. 7238 of the Clemson University Experiment Station.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Aycock, R. Stem rot and other diseases caused by *Sclerotium rolfsii*. *N. C. Agric. Exp. Stn. Tech. Bull.* **1966**, *175*, 1–202.
2. Backman, P.A.; Brenneman, T.B. Peanut Diseases. In *Compendium of Peanut Diseases*, 2nd ed.; Kokalis-Burelle, N., Porter, D.M., Rodrigues-Kabana, R., Smith, D.H., Subrahmanyam, P., Eds.; American Phytopathological Society Press: St. Paul, MN, USA, 1997.
3. Standish, J.R.; Culbreath, A.K.; Branch, W.D.; Brenneman, T.B. Disease and yield response of a stem-rot-resistant and -susceptible peanut cultivar under varying fungicide inputs. *Plant Dis.* **2019**, *103*, 2781–2785. [CrossRef] [PubMed]
4. Bowen, K.L.; Hagan, A.K.; Weeks, J.R. Soil-borne pests of peanut in growers' fields with different cropping histories in Alabama. *Peanut Sci.* **1996**, *23*, 36–42. [CrossRef]
5. Mehan, V.K.; Mayee, C.D.; McDonald, D. Management of *Sclerotium rolfsii*-caused stem and pod rots of groundnut-a critical review. *Int. J. Pest Manag.* **1994**, *40*, 313–320. [CrossRef]
6. Mullen, J. Southern blight, southern stem blight, white mold. *Plant Health Instr.* **2001**, *10*, 104. [CrossRef]
7. Anco, D.; Marshall, M.; Kirk, K.R.; Plumblee, M.T.; Smith, N.; Mickey, S.; Farmaha, B.; Payero, J. *Peanut Money-Maker 2024. Production Guide; Circular 588*; Clemson University Extension: Clemson, SC, USA, 2024.
8. Augusto, J.; Brenneman, T.B.; Culbreath, A.K.; Sumner, P. Night spraying peanut fungicides I. Extended fungicide residual and integrated disease management. *Plant Dis.* **2010**, *94*, 676–682. [CrossRef]
9. Augusto, J.; Brenneman, T.B.; Culbreath, A.K.; Sumner, P. Night spraying peanut fungicides II. Application timings and spray deposition in the lower canopy. *Plant Dis.* **2010**, *94*, 683–689. [CrossRef] [PubMed]
10. Woodward, J.E.; Brenneman, T.B.; Mullinix, B.G., Jr. Irrigation timing impacts the efficacy of foliar-applied fungicides toward foliar and soilborne pathogens of peanut. *Plant Dis.* **2012**, *96*, 1785–1790. [CrossRef] [PubMed]
11. Davis, R.F.; Smith, F.D.; Brenneman, T.B.; McLean, H. Effect of irrigation on expression of stem rot of peanut and comparison of aboveground and belowground disease ratings. *Plant Dis.* **1996**, *80*, 1155–1159. [CrossRef]
12. Bowen, K.L. Development of stem rot (caused by *Sclerotium rolfsii*) in peanut in Alabama. *Peanut Sci.* **2003**, *30*, 120–128. [CrossRef]
13. Sanjel, S.; Colee, J.; Barocco, R.L.; Dufault, N.S.; Tillman, B.L.; Punja, Z.K.; Seepaul, R.; Small, I.M. Environmental factors influencing stem rot development in peanut: Predictors and action thresholds for disease management. *Phytopathology* **2024**, *114*, 393–404. [CrossRef] [PubMed]
14. Renfroe-Becton, H.; Croft, J.; Davis, C.; Varn, J.; Culbreath, A.K.; Langston, D.B.; Anco, D.J. Phenotypic fungicide resistance and cross-resistance among *Nothopassalora personata* populations. *PhytoFrontiers* **2024**. [CrossRef]
15. Culbreath, A.K.; Brenneman, T.B.; Kemerait, R.C., Jr.; Stevenson, K.L.; Anco, D.J. Combinations of elemental sulfur with demethylation inhibitor fungicides for management of late leaf spot (*Nothopassalora personata*) of peanut. *Crop Protect.* **2019**, *125*, 104911. [CrossRef]
16. Culbreath, A.K.; Brenneman, T.B.; Kemerait, R.C., Jr.; Cantonwine, E.G. Comparison of elemental sulfur products as tank mix partners with azoxystrobin for management of late leaf spot (*Nothopassalora personata*) of peanut. *Plant Health Prog.* **2023**, *24*, 188–192. [CrossRef]

17. Simmonds, M.C.; Higgins, J.P.T.; Stewart, L.A.; Tierney, J.F.; Clarke, M.J.; Thompson, S.G. Meta-analysis of individual patient data from randomized trials: A review of methods used in practice. *Clin. Trials* **2005**, *2*, 209–217. [CrossRef] [PubMed]
18. Thompson, S.G.; Higgins, J.P.T. How should meta-regression analyses be undertaken and interpreted? *Stat. Med.* **2002**, *21*, 1559–1573. [CrossRef]
19. van Houwelingen, H.C.; Arends, L.R.; Stijnen, T. Advanced methods in meta-analysis: Multivariate approach and meta-regression. *Stat. Med.* **2002**, *21*, 589–624. [CrossRef] [PubMed]
20. Brooks, M.E.; Kristensen, K.; van Benthem, K.J.; Magnusson, A.; Berg, C.W.; Nielsen, A.; Skaug, H.J.; Maechler, M.; Bolker, B.M. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *R J.* **2017**, *9*, 378–400. [CrossRef]
21. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2023. Available online: https://www.R-project.org/ (accessed on 1 November 2023).
22. Lin, L.I.-K. A concordance correlation coefficient to evaluate reproducibility. *Biometrics* **1989**, *45*, 255–268. [CrossRef]
23. Huber, L.; Madden, L.V.; Fitt, B.D.L. Rain-splash and spore dispersal: A physical perspective. In *The Epidemiology of Plant Diseases*; Jones, D.G., Ed.; Springer: Dordrecht, The Netherlands, 1998. [CrossRef]
24. Madden, L.V. Effects of rain on splash dispersal of fungal pathogens. *Can. J. Plant Pathol.* **1997**, *19*, 225–230. [CrossRef]
25. Pietravalle, S.; van den Bosch, F.; Welham, S.J.; Parker, S.R.; Lovell, D.J. Modelling of rain splash trajectories and prediction of rain splash height. *Agric. For. Meteorol.* **2001**, *109*, 171–185. [CrossRef]
26. Shaw, M.W. Assessment of upward movement of rain splash using a fluorescent tracer method and its application to the epidemiology of cereal pathogens. *Plant Pathol.* **1987**, *36*, 201–213. [CrossRef]
27. Shew, B.B.; Beute, M.K.; Campbell, C.L. Spatial pattern of southern stem rot caused by *Sclerotium rolfsii* in six North Carolina peanut fields. *Phytopathology* **1984**, *74*, 730–735. [CrossRef]
28. Chapman, S.C.; Ludlow, M.M.; Blamey, F.P.C.; Fischer, K.S. Effect of drought during pod filling on utilization of water and on growth of cultivars of groundnut. *Field Crops Res.* **1993**, *32*, 243–255. [CrossRef]
29. Munir, M.; Wang, H.; Agudelo, P.; Anco, D.J. Rapid detection of fungicide resistance phenotypes among populations of *Nothopassalora personata* in South Carolina peanut fields. *Plant Health Prog.* **2020**, *21*, 123–132. [CrossRef]
30. Anco, D.J.; Thomas, J.S.; Jordan, D.L.; Shew, B.B.; Monfort, W.S.; Mehl, H.L.; Small, I.M.; Wright, D.L.; Tillman, B.L.; Dufault, N.S. Peanut yield loss in the presence of defoliation caused by late or early leaf spot. *Plant Dis.* **2020**, *104*, 1390–1399. [CrossRef]
31. Brent, K.J.; Hollomon, D.W. *Fungicide Resistance in Crop Pathogens: How Can It Be Managed?* 2nd ed.; Fungicide Resistance Action Committee Monograph No. 1; Global Crop Protection Federation: Brussels, Belgium, 2007; ISBN 90-72398-07-6.
32. Deising, H.B.; Reimann, S.; Pascholati, S.F. Mechanisms and significance of fungicide resistance. *Braz. J. Microbiol.* **2008**, *39*, 286–295. [CrossRef]