Final Report:
Epidemiological modeling of soybean grower responses to production practices

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Building from the NCSRP-funded project, "Benchmarking soybean production systems in the North-Central USA," the goal of this project was to conduct a comprehensive statistical analysis to examine specific factors that may be driving foliar fungicide response given the large-producer provided data. Our approach was to conduct a comprehensive analysis of individual factors driving yield, all with the goal to build a causal model that explains the response, which in this case was yield, as a function of specific practices organized in a logical fashion considering farmer production practices.

In this report, we examined specific factors that drive yield, as well as the potential role or influence in explaining yield response due to the foliar fungicides. We continue to work on the causal model and the information presented in this report represents key components considered in the analysis. We also have a working document that is approximately 380 pages that highlights the entire work on this project. Specific questions, computational code, and results that are not in this report can be assessed by contacting the research team.

Background dataset. Data were provided from the "Benchmarking soybean production systems in the North-Central USA" research team. Our work focused on the period, 2014-2016. We will most likely update the database with 2017 (and further) data in the future to continue to test and validate models developed from this initial work. Overall, the database consisted of 5,284 fields, and there were 74 columns consisting of identification variables, yield, and additional variables considered to be potentially associated with yield for each field (Figure 1). Average field size was 86 acres (3 to 994-acre range) and this variable was not correlated with yield.

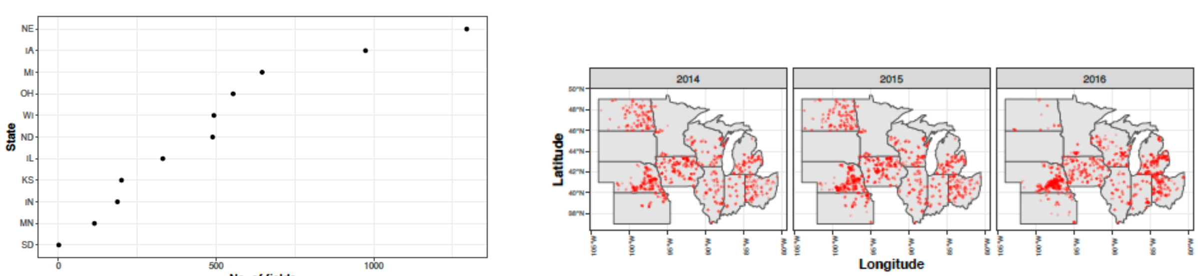

Figure 1. Number of fields and relative distribution by state that were included in statistical analyses. These observations represented the period 2014-2016.

Key findings for agronomic factors driving yield. In the following sub-sections, we will highlight specific cultural and management tactics and their relative contribution to yield. The section starts with foliar fungicides and insecticides, since that was the primary question of interest. From there, we examined the relative importance of other factors to help explain the observed response to foliar fungicides.

A. **Foliar insecticides and/or fungicides.** Our main question with this factor, beyond the primary goal of the project, is also to get at the underlying explanation for a response to foliar fungicides. We have built this into several sub-questions as we mined the data:

    a. Are insecticides/fungicides the *cause* of yield increase?
    b. Or, is the use of one or more of these management tools *associated* with high-yield situations, which means that are "embedded" or confounded with other production factors?
    c. Why are growers using insecticides/fungicides, given that the majority of fields are *not* sprayed?
    d. If these treatments are truly giving a response, then why is the adoption not higher?

Foliar insecticides were applied around approximately 27.5% of fields. Proportion of application at the state level varied, ranging from just over 10% in Michigan to around 90% in Minnesota. Yield showed a general increase across all states (Figure 1). A similar trend was observed when stratifying the date by soybean maturity group (MG).

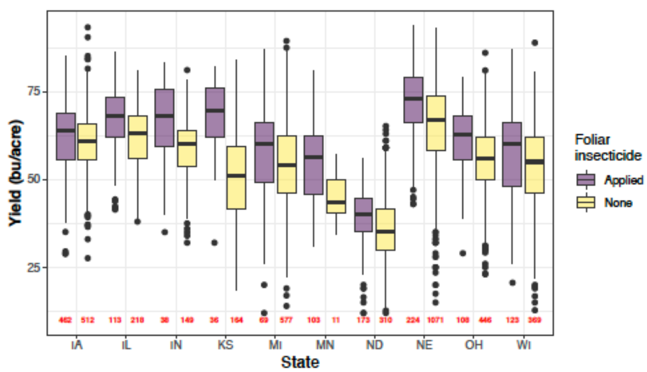

Figure 1. Yield as a function of foliar insecticide application across states.

Foliar fungicide use was documented in approximately 25.9% of farmer fields. The proportion of fields receiving an application varied, but not to the same extent as we observed for foliar insecticides. The range was 11.4% (Minnesota) to 46.2% (Iowa). We also looked at the question of whether fields under irrigation, and therefore potentially at higher risk for diseases like white mold received a greater proportion of fungicide applications. Results indicated no differences (P = 0.6765, based on a chi-square test). Furthermore, the proportion of fields receiving a foliar fungicide application was lower in the highest seeding rate category. There was a slight difference in the number of fields using a 30-inch row spacing that were sprayed but numerically these differences were small. Nonetheless, there was a general association between fungicide application and yield (Figure 2) and we also observed a similar trend as seen for foliar insecticides across MG.

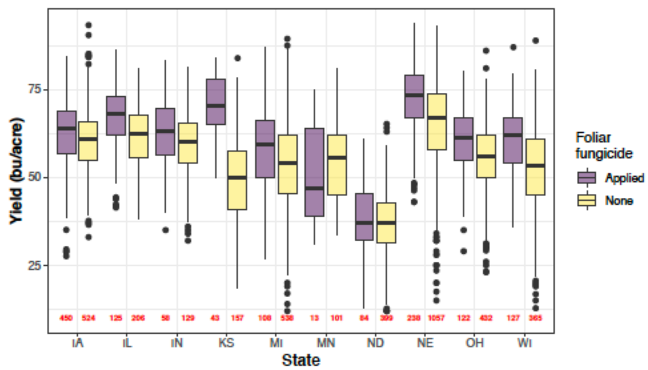

Figure 2. Yield as a function of foliar fungicide application across states.

Part of the reason for the similar trends is probably due to the fact that about 18.3% of the fields received both a foliar fungicide and foliar insecticide. Stratifying the yield response by state and type of foliar spray application (insecticide, fungicide, both), yield was variable across states (Figure 3). Across MG, there was again some variability in the response although for several maturity groups highest yields were observed with the "both" application.

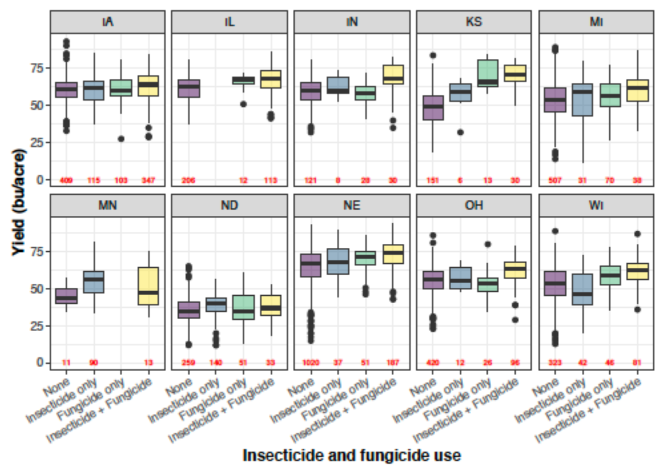

Figure 3. Yield as a function of foliar fungicide, foliar insecticide, or both, stratified by state.

B. **Irrigation.** Irrigation is considered as a yield-influencing factor, although this was strongly tied to geography, for example, Nebraska (Figure 4). Pivot irrigation is the most popular irrigation system (Figure 4), and results indicated that over-irrigating did not increase yield (Figure 5).

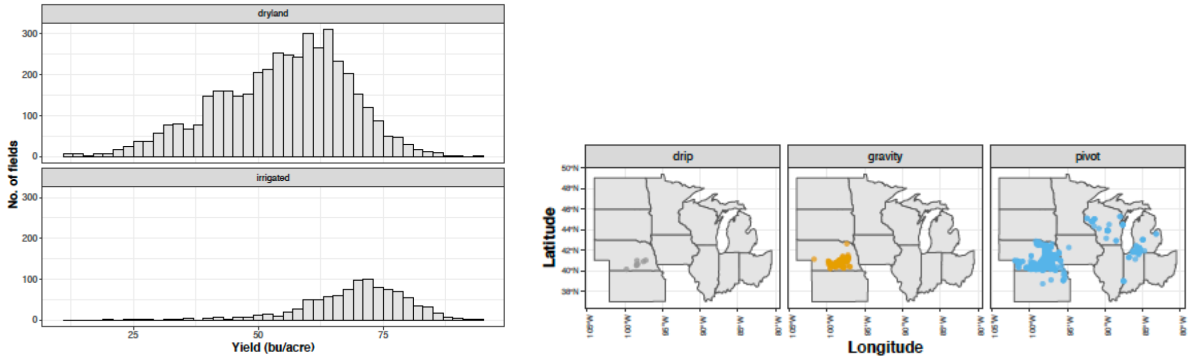

Figure 4. Yield as a function irrigation type. For the histogram, yield was separated by dryland (top) and irrigated (bottom), while the map illustrates the spatial location and use of different irrigation systems.

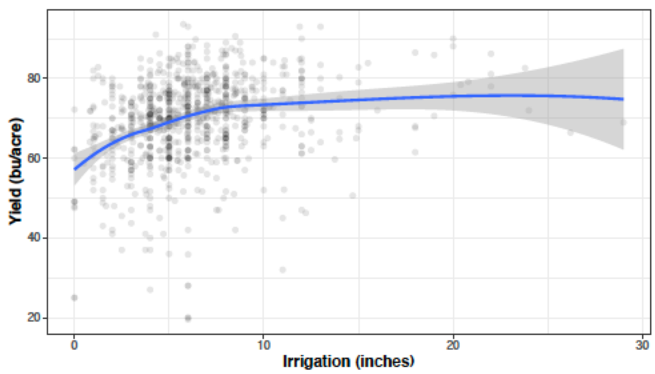

Figure 5. Yield as a function of the amount of irrigation in inches.

C. **Soybean maturity group (MG).** What should not be considered a major surprise, latitude influenced the MG most suitable for their location (Figure 6).

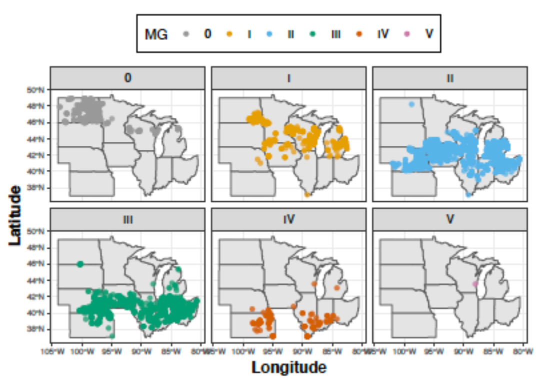

Figure 6. Field locations stratified by maturity group.

Growers are optimizing MG based on their geographic location, which is also important for quantifying the eventual impact of foliar fungicides as a function of geography (MG) since that defines different yield potentials (Figure 7).

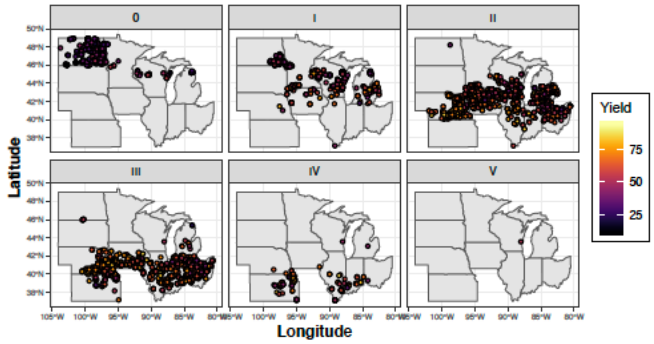

Figure 7. Soybean yield stratified spatially and by maturity group.

D. **Herbicide trait.** In this situation, of the 4,388 fields where a herbicide trait was reported, 96.5% were Roundup Ready. We do not expect this then to contribute greatly to yield with foliar fungicides, in the general sense, since it has been a practice uniformly adopted.

E. **Row spacing.** The main finding is that regional context is important. Furthermore, we found no evidence that narrow (15-inch) row spacing benefited yield over wider (30-inch) row spacing (Figure 8).

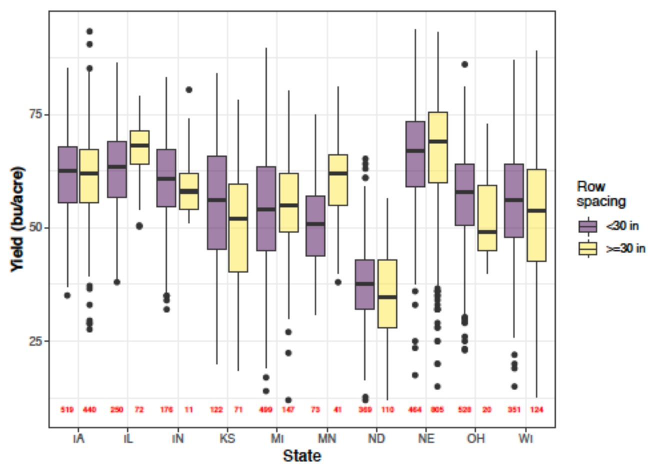

Figure 8. Yield as a function of row spacing.

As illustrated in Figure 9, irrigation (water availability) was considered as a more influential parameter than row spacing.

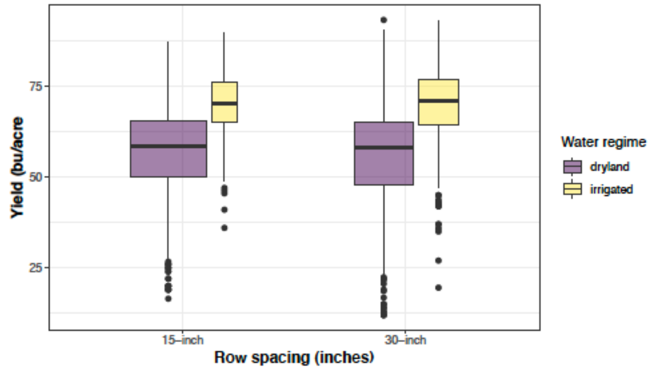

Figure 9. Yield as a function of row spacing and water regime.

F. **Early planting is beneficial.** Early planting increased soybean yield, with highest yields observed with April plantings (Figure 10). Obviously, the impact of early planting is relative, especially considering maturity group and geography. Nonetheless, this is an important factor considering potential impact of foliar fungicides, since planting date can be defined in the context of different critical periods during the growing season when foliar fungicides may be more effective.

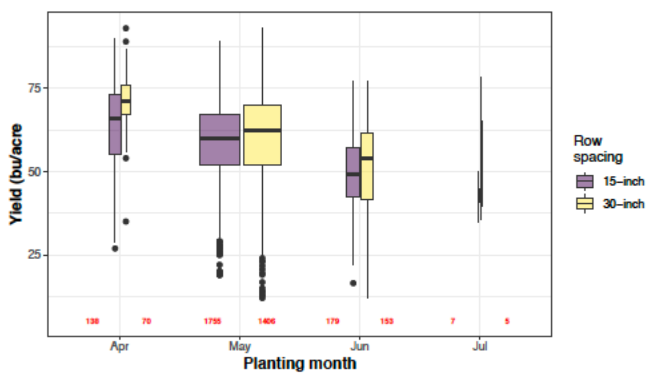

Figure 10. Yield as a function of planting date and row spacing.

G. **Seed treatments against pests.** Approximately 70% of fields were sown to fungicide-treated seed. Additionally, 64% of fields had an insecticide-seed treatment (page 69). This mirrors trends seen in other studies, as well as our own preliminary results from examining the USDA Pesticide National Synthesis Project (https://water.usgs.gov/nawqa/pnsp/usage/maps/). This implies that growers are looking to get good establishment, which may link to planting date and also growth and development that could impact foliar disease risk.

H. **Rotations.** Over 84% of responses indicated that corn was the previous crop, which is important for considering how rotations influence disease risk in soybean.

I. **Tillage.** As reported, approximately 48% of fields were produced using no-till methods, with a very wide distribution across the region (Figure 11).

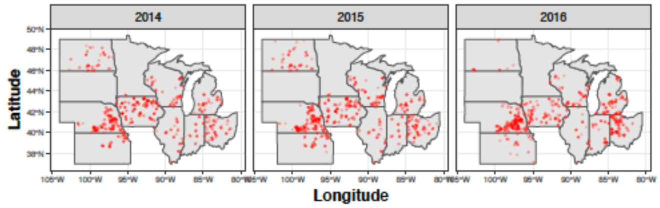

Figure 11. Spatial distribution of no-till soybean fields.

This may be an important factor for disease risk given the survivability of many soybean pathogens in crop residue. Interestingly, there did not appear to be any reported yield penalty as a function of no-till (Figure 12).

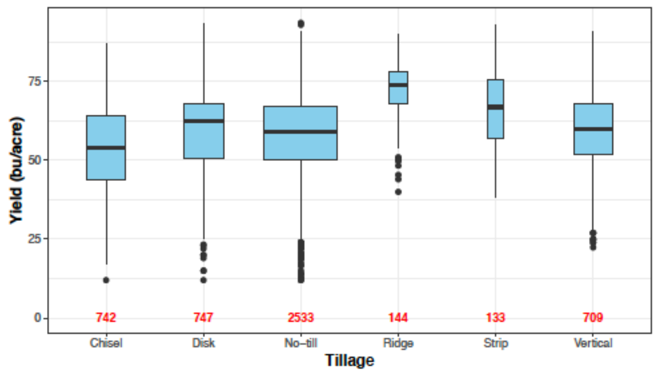

Figure 12. Yield as a function of tillage type.

J. **Manure.** In general, N-fertilization of fields is not recommended. Data from the farmers also show this, as only 7.8% of all fields had a manure application, and those were concentrated in Iowa and Minnesota. We expect this factor to have limited predictive value.

K. **Topsoil pH and yield.** Yield was impacted by pH (Figure 13), which will be important to consider in terms of disease and the likely influence of abiotic/physiological factors on the use of foliar fungicides. Lowest yields were observed with pH greater than 7.0.

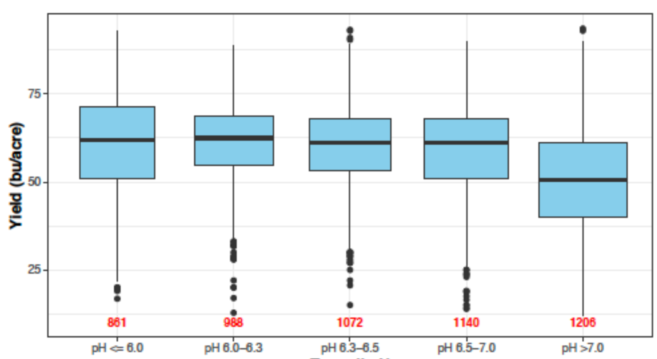

Figure 13. Yield as a function of pH category.

L. **Plant available water holding capacity in the root zone (PAWR).** Increased moisture availability does improve yield (Figure 14), which may also relate to potential risk for soybean diseases. Nonetheless, we will be looking at this variable and how well it relates to spatial aspects of the yield response profile.

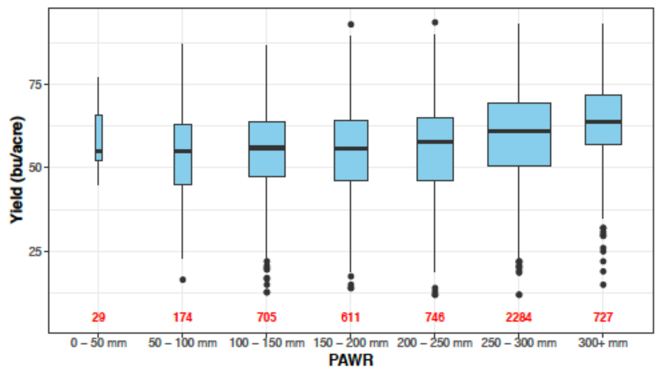

Figure 14. Yield as a function of plant available water holding capacity in the root zone (PAWR).

Key findings for phenological factors driving yield. In this section, our focus was on trying to understand phenology and how it related with yield as a function of disease risk and foliar fungicide use. Our efforts focused on questions related to time to emergence (quality of soybean establishment) to time related to specific critical periods that relate to some of the foliar diseases like Septoria brown spot or Frogeye leaf spot, as two examples.

A. **Time spent from R3 to R7 is related to yield.** Figure 15 shows the number of days spent between R3 and R7 with soybean maturity group. Increased time in the reproductive phase showed increase yield. Time spent between these two critical group stages may be a proxy for things like nutrient uptake, photosynthetic productivity, as well as providing information about the "risk window" for foliar diseases.

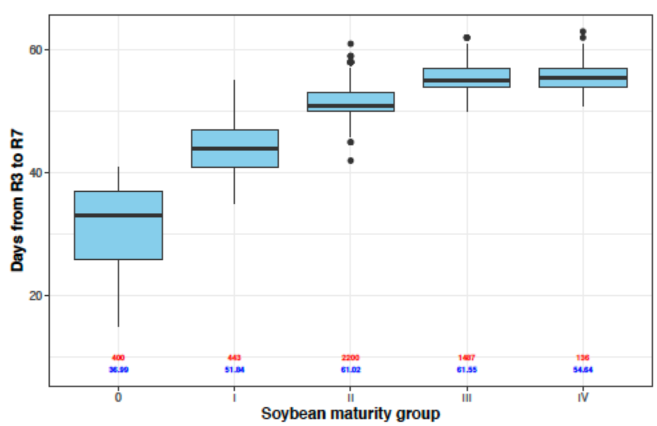

Figure 15. Yield as a function of the number of days between R3 and R7, stratified by maturity group.

In Figures 16 and 17, we show the yield trends in two different manners. Figure 16 stratifies the response by maturity group and the use of foliar fungicides, while for Figure 17, we have the time (in days) between R3 and R7 stratified by state and use of foliar fungicide. Results are less consistent in Figure 17, meaning that it is not clear that a fungicide application lengthened the grain fill period. A similar observation was made when stratifying the time between R3 and R7 (as well as from emergence to R3) by maturity group and foliar fungicide application.

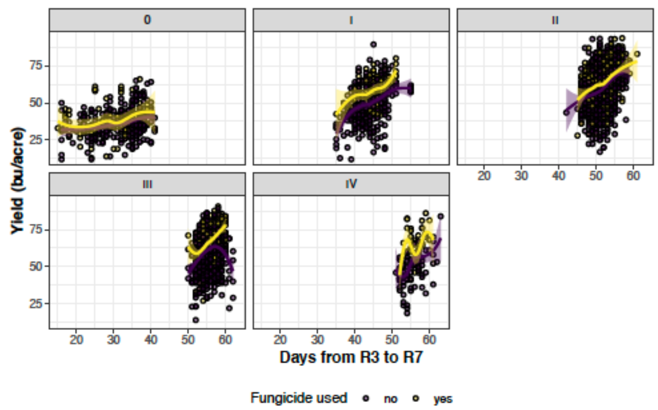

Figure 16. Yield trends as a function of the number of days between R3 and R7, stratified by maturity group and the use of foliar fungicides.

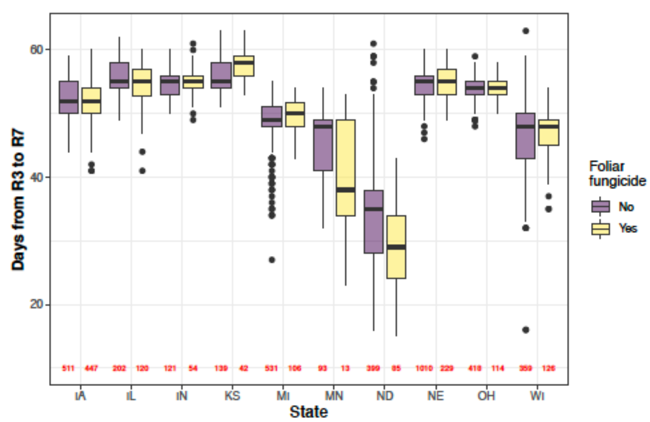

Figure 17. The number of days between R3 and R7, stratified by state and the use of foliar fungicides.

B. **Weather and phenology.** For each field, given the phenological dates, we calculated various weather variable summaries (e.g. mean temperature) for the different growth periods. Plants receive the most influx of radiation (light) during growth from emergence to R3, but there are pronounced differences among the MGs because of latitude. Total daylight and total incident shortwave radiation flux density are related. Temperature stress was more likely to occur during growth from R3 to R7.

C. **Weather and yield.** While there were many variables examined that did not appear to clearly relate with yield, we noticed some specific variables that were deemed important and can be considered as explanatory variables for fungicide application. The majority of these variables related to the R3 to R7 growth period.

C.(1). Total precipitation from the beginning of R3 to the beginning of R7 (Figure 18). In MGs 3 and 4, there was a clear difference in terms of the yields with increasing total precipitation, and fungicide use also showed a difference with the "no" application situation.

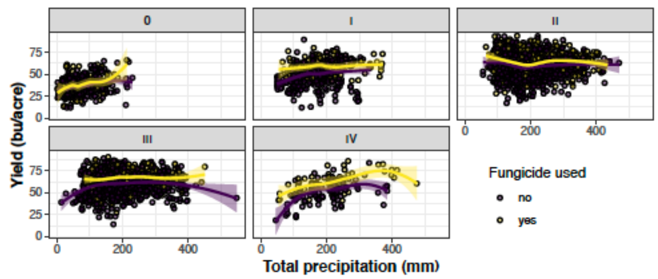

Figure 18. Yield as a function of total precipitation between the R3 and R7 growth stages, stratified by maturity group.

C.(2). Mean of the daily minimum temperature from the beginning of R3 to the beginning of R7 (Figure 19). Mean daily temperature likewise showed increasing trends with yield, although the effect of foliar fungicide was less clear, depending on MG.

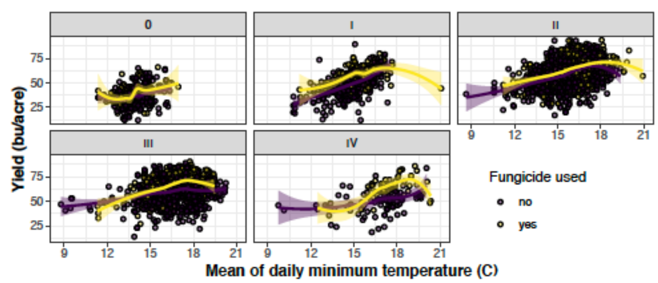

Figure 19. Yield as a function of the mean of the daily minimum temperature between the R3 and R7 growth stages, stratified by maturity group.

C.(3). Sum of daily minimum temperature from the beginning of R3 to the beginning of R7 (Figure 20). There was a positive trend between the sum of daily minimum temperature during the R3 to R7 growth period and depending on MG the effect of foliar fungicide was different.

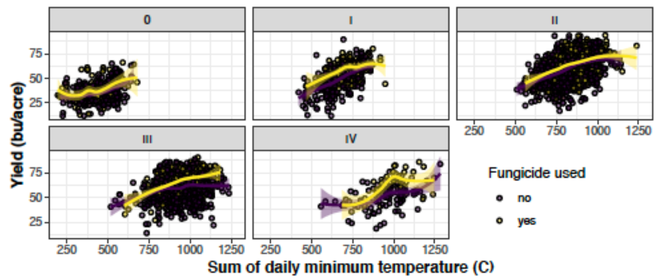

Figure 20. Yield as a function of the sum of daily minimum temperature between the R3 and R7 growth stages, stratified by maturity group.

C.(4). Mean of the daily maximum temperature from the beginning of R3 to the beginning of R7 (Figure 21). There was a general linear trend between yield and mean daily maximum temperature although a negative effect of high temperature was also noted across multiple MGs. Fungicide gave some variable results across the MGs.

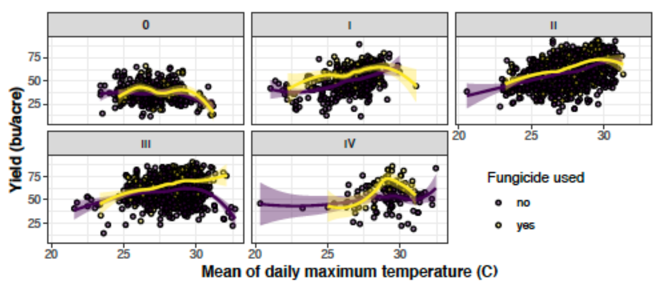

Figure 21. Yield as a function of the mean daily maximum temperature between the R3 and R7 growth stages, stratified by maturity group.

C.(5). Sum of daily maximum temperature from the beginning of R3 to the beginning of R7 (Figure 22). For MG 1 and MG 2, there was a positive trend between the sum daily maximum temperature and yield, while for MG 3 and MG 4, there was a negative impact (heat stress) with increased high temperatures. Foliar fungicide response was less clear for MGs 0, 1, or 2, but there did appear to be a positive result in MG 3 and MG 4, which warrants additional consideration as related to disease risk.

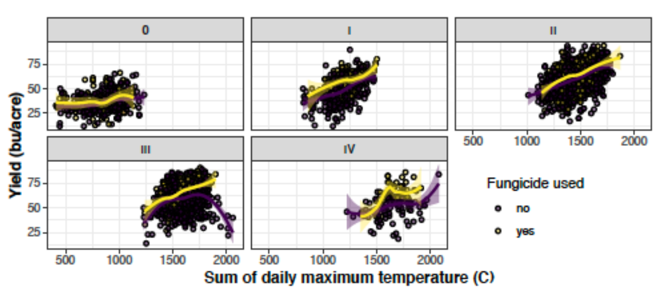

Figure 22. Yield as a function of the sum of daily maximum temperature between the R3 and R7 growth stages, stratified by maturity group.

C.(6). Mean of daily average temperature from the beginning of R3 to the beginning of R7 (Figure 23). Yield showed a quadratic or nonlinear relationship across MG. There does appear to be a higher yield with fungicide application especially for temperatures between 20 and 25 C.

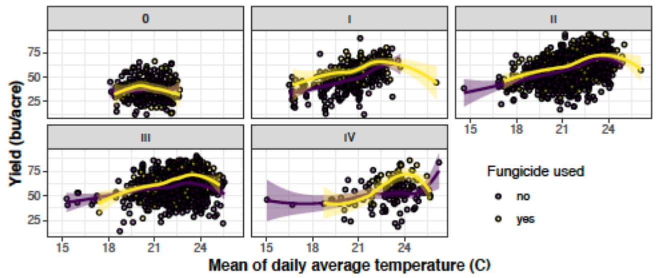

Figure 23. Yield as a function of the mean of the daily average temperature between the R3 and R7 growth stages, stratified by maturity group.

C.(7). Sum of daily average temperature from the beginning of R3 to the beginning of R7 (Figure 24). For MGs 1 to 4, yield was positively correlated with increased temperature units. Yield also was higher in general with the use of a foliar fungicides, similar to other temperature measures.

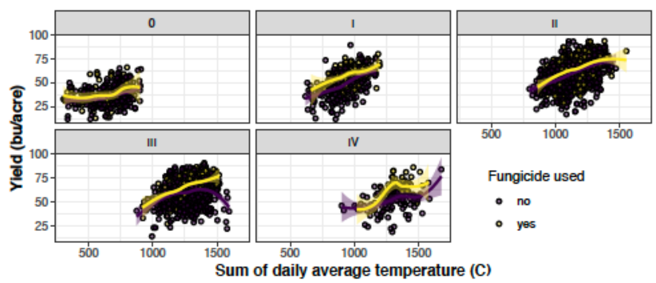

Figure 24. Yield as a function of the sum of the daily average temperature between the R3 and R7 growth stages, stratified by maturity group.

From a technical standpoint. Given that **there were several different types of variables** and also given that **some of the data do not support some common perceptions or reports** published on the subject of using foliar fungicides in soybean, we were hesitant about just throwing a whole bunch of variables into a machine learning algorithm without some previous screening through the types of exploratory analyses we have been doing. Our overall working document for summarizing the results is over 380 pages, as indicated earlier. This information can be requested directly from the research team and as we finish papers on the subject will be made available back to the broader soybean community.

Publications and presentations.

1. How management decisions impact the disease cycle and disease risk, Penn State Extension Workshops and Programs, Keystone Crops and Soils Conference, Grantville,

PA, 20 participants, (October 24, 2018).

2. Disease identification and fungicide application, Penn State Extension Workshops and Programs, Instructor, Penn State Extension, Rock Springs, PA, 75 participants. (August 29, 2018).
3. Soybean disease management, Penn State Extension Workshops and Programs, Instructor, Pennsylvania Corn and Soybean Conference, Grantville, PA, 75 participants. (February 22, 2018).
4. Fungicides on corn and soybean: Updated yield results and considerations for use, Penn State Extension Workshops and Programs, Instructor, Extension Program, Pennsylvania Agronomic Education Conference, Harrisburg, PA, 55 participants, Both, Academic. (January 16, 2018).
5. Esker, P., and Shah, D. 2019. Manejo de datos difíciles en R: consejos desde las trincheras (Data wrangling in R: Tips from the trenches). ConectaR Conference, San Pedro Montes de Oca, Costa Rica.
6. Butts, T., et al. (working paper). Evaluation of underlying factors impacting soybean yield response to foliar fungicide applications across the North-Central United States.
7. Shah, D., et al. (working paper). Causal modeling to determine the underlying patterns of yield response to foliar fungicide applications in soybean across the North-Central United States.