Neonicotinoid soybean seed treatments provide negligible benefits to US farmers

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In a bean pod:

- Across the entire region, the maximum average observed yield benefits due to fungicide (FST = fungicide seed treatment) + neonicotinoid use (FST+NST) reached 2 bu/ac.
- Specific combinations of management practices minimally increased the effectiveness of FST+NST by 0.2 to 3.3 bu/ac.
- Across the entire region, a partial economic analysis showed inconsistent evidence of a break-even cost of FST or FST+NST.
- These results demonstrate that the current widespread prophylactic use of NST in the key soybean-producing areas of the US should be re-evaluated by producers and regulators alike.

Introduction

In the US, the most recent published estimates reflect that approximately 34-44% of planted soybean acreage are treated with neonicotinoid seed treatments (NST) (Douglas & Tooker, 2015). Based upon trendlines shown in that work, the current estimate for NST use in soybeans is very likely to exceed 50%. Insecticidal seed treatments of soybean belong to the neonicotinoid class of insecticides that include the active ingredients clothianidin, imidacloprid, and thiamethoxam. Corn and soybean seed treatments represent the largest uses of neonicotinoids nationally, and the higher seeding rate of soybeans mean that they are responsible for the highest levels of active ingredient per unit area (USGS, 2014). It is notable that current NST use rates far exceed historic benchmarks for insecticide use in soybeans; in the decade prior to introduction of neonicotinoid seed treatments, only about 5% of soybean acres received insecticides (Fernandez-Cornejo et al., 2014). This benchmark reflects that the region where most of US soybeans are grown, the upper Midwest, benefits from a temperate climate and relatively few insect pests, particularly in the early season when NST would provide most crop protection. Recent reviews of insect pest abundance in soybean re-confirm this assessment – early season pests of soybean are still infrequently encountered across the region (Hesler et al., 2018; Papiernik et al., 2018). Soybean aphid, a relatively recent invader to US soybean production, is a notable exception, but it's distribution and phenology are a poor fit for the early-growing season, when NST are most effective (Krupke et al., 2017).

Recent studies report weak relationships between NST use and effectiveness in preserving crop yield. Specifically for soybean, in a recent multi-environment study in Wisconsin, yield benefit due to the use of insecticide seed treatments was variable (Gaspar et al., 2014). A recent multi-state study of management tactics for the key pest in the region, the soybean aphid (*Aphis glycines* Matsumura) demonstrated that crop yield benefits and overall economic returns were marginally affected by NST, while an integrated pest management (IPM) approach, which combined scouting for the pest with foliar insecticide sprays only when the established economic threshold is reached, proved superior in all metrics outlined above (Krupke et al., 2017). Aside from the fact that a farmer may be incurring unnecessary input costs, a growing body of research suggests that the use of NST in this manner can lead to a host of negative effects upon non-target organisms. Studies in the US and elsewhere have evaluated impacts of neonicotinoid on nontarget organisms such as honey bees (Sánchez-Bayo et al., 2016) wild bees (Woodcock et al., 2016), monarch butterflies (Pecenka & Lundgren, 2015), vertebrates (Hoshi et al., 2014), terrestrial and aquatic invertebrates (Pisa et al., 2015), key predators of soybean pests (Douglas et al. 2014) and overall declines in ecosystem function (Chagnon et al., 2015). Although each of these concerns are relevant to the US soybean-producing regions, it is worthwhile to note that key soybean producing states represented in our study include SD and MN which rank 4th and 5th, respectively in honey bee colonies ranked by state; many of these are migratory colonies used for pollination of key fruit and nut crops. This presents a key intersection between NST exposure and our principal managed pollinator species with demonstrated sensitivity to this class of compounds.

When implementing an IPM approach, an insecticide is used only when pest populations are expected to reach economically important populations and other management tools are not available or effective (Lewis et al., 1997). Using NST under an IPM strategy is challenging due to a lack of secondary pest monitoring and predictive tools and thus, limited predictive power regarding early season pest populations. Consequently, the approach to NST use in North American annual crops since their introduction in the early 2000's has been a continent-wide test of an "insurance-based" approach to insect pest management, where the risk of pests across the entire soybean-growing region was assumed to be sufficient to justify the use of insecticide over tens of millions of acres annually, without corroborating monitoring or real-time yield assessments. This study uses a large, region-wide dataset to evaluate this approach.

Materials and Methods

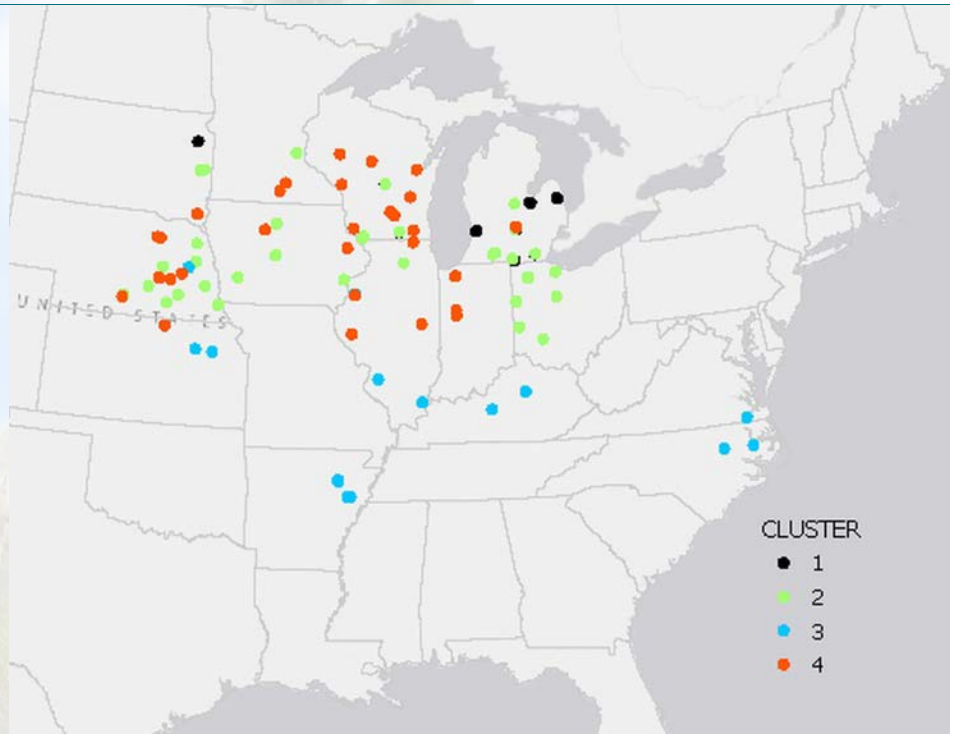
Soybean seed yield data from 194 randomized and replicated field studies, conducted specifically to evaluate the effect of seed treatments on soybean seed yield at sites within each of 14 states from 2006 through 2017, were assembled for this study. The final database included 11,146 plot-specific soybean seed yields. For all experiments, weather data, soil pH and information about nine major management practices, including irrigation, planting date, cultivar maturity group, tillage operations, previous year crop, row spacing, seeding rate, double crop system, and manure application were recorded.

Since individual experiments were located in different regions, the effect of environment on soybean yield was assumed to be significant. Mixed models were used to quantify the effect of seed treatments on soybean seed yield. For the partial economic analysis, yield in every plot in every trial with seeding rate of 100,000, 140,000, or 180,000 seeds/ac were converted to profit for five soybean price scenarios: 8, 11, 14, 17, and 20 \$/bu. Then, the profit for each scenario (seeding rate × seed treatment (FST, FST+NST, UTC) × soybean price) was used as dependent variable in a mixed model analysis.

Results and Discussion

The soybean seed yield data from 194 studies were stratified in four growing environments (Fig. 1) based on soil pH and in-season weather conditions. There were differences in average growing season temperatures and total precipitation among the four clusters. The greatest precipitation occurred in locations in clusters 2 and 3. Locations in cluster 4 had the lowest precipitation and greatest average yields were observed in cluster 2.

Figure 1. Location of individual experiments that were included in the study. Experiments with the same color belong to a cluster with similar growing environments.

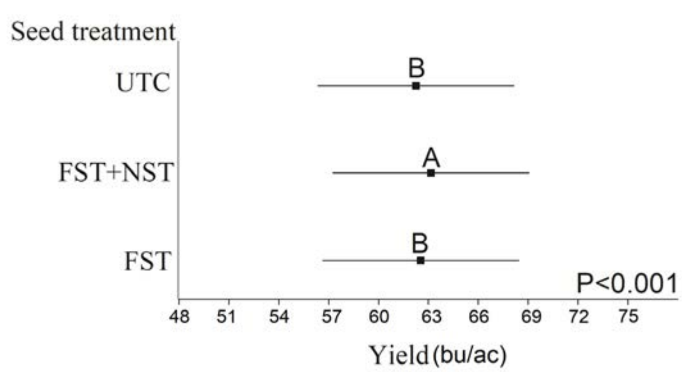


FST, FST+NST, and untreated controls (UTC) were applied in all locations. Across the entire region, concurrent use of FST+NST effectively increased soybean yield compared to FST and UTC seed (Fig. 2). Nevertheless, the maximum yield difference compared with fungicide only and from untreated seed was small and reached only 0.6 and 0.9 bu/ac, respectively. Similar magnitudes of yield differences were observed within clusters 1, 2 and 4 where the effect of seed treatment was significant.

When repeating the analysis with seed treatments separated by neonicotinoid active ingredients (imidacloprid, thiamethoxam, and clothianidin), across the entire region, concurrent thiamethoxam-based FST+NST resulted in the highest yield (~65 bu/ac), and differences compared with the other seed treatments did not exceed 2 bu/ac (Fig 3). A similar magnitude of yield differences due to seed treatments, separated by neonicotinoid active ingredients, was observed within each cluster. These results suggest that the yield benefit due to neonicotinoid seed treatments was small but relatively consistent across the entire study area.

Conditional inference tree analysis was used to identify conditional effects of seed treatments with growing environments (clusters) and management practices. Irrigation, followed by cluster, were the most important yield limiting factors followed by the effect of row spacing and seeding rate (Fig. 3). In cluster 1, narrow rows in non-irrigated experiments were associated with yield increase by up to 4.5 bu/ac whereas in cluster 2, seeding rate greater than 120,000 seeds/ac resulted in the greatest yield.

Figure 2. Soybean yield (bu/ac) due to the applied seed treatments across the entire region. The black rectangles show the mean yield for each treatment and the lines extend to the lower and upper 95% confidence limits. Note: FST, fungicide only; FST+NST, fungicide plus neonicotinoid insecticide; UTC, untreated control. Means with the same letter are not significantly different at α=0.05.



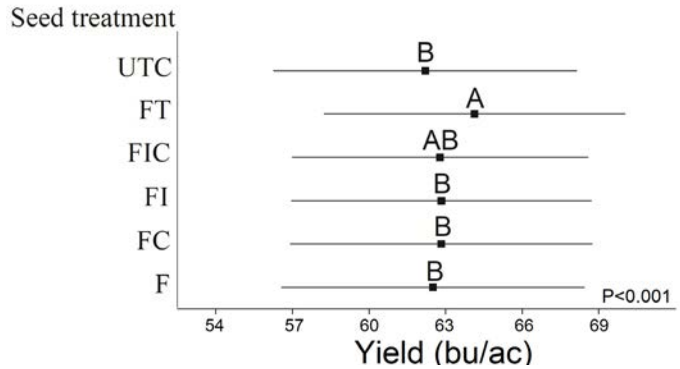


Figure 3. Soybean yield (bu/ac) due to the applied seed treatments across the entire region. The black rectangles show the mean yield for each treatment and the lines extend to the lower and upper 95% confidence limits. Note: F, fungicide only; FT, fungicide plus insecticide (thiamethoxam); FI, fungicide plus insecticide (imidacloprid); FC, fungicide plus insecticide (clothianidin); FIC, fungicide plus insecticide (imidacloprid + clothianidin); UTC, untreated control. Means with the same letter are not significantly different at α=0.05.

When repeating the analysis, with treatments separated by neonicotinoid active ingredient (imidacloprid, thiamethoxam, and clothianidin), the results were identical to Fig 4. This analysis demonstrates that seed treatments evaluated here, with and without neonicotinoids, have a negligible effect on soybean yield. In all experiments included in this study, the effectiveness of NST was examined concurrently with FST. This is a common practice (51% of treated fields) among farmers across the North-central US (Edreira et al., 2017), and our results suggest that such a practice is unlikely to significantly increase economic yields across the region. Based on these analyses, we conclude that prophylactic use of seed treatments (with and without neonicotinoids) are not necessary to maximize yield returns across the region, and other management practices that have a more direct impact on soybean seed yield, are more important considerations (Mourtzinis et al., 2018), these include planting date, and cultivar maturity group.

The effectiveness of the combined FST+NST compared with the FST alone appeared to be affected mainly by the use of row spacing, irrigation, and the cultivar's maturity group (Fig. 5 A). The greatest yield benefit of NSTs was observed in 12% of cropping systems that included non-irrigated plants in narrow rows (15 inches) and cultivars with maturity group ≤ 2 (+2.8 bu/ac).

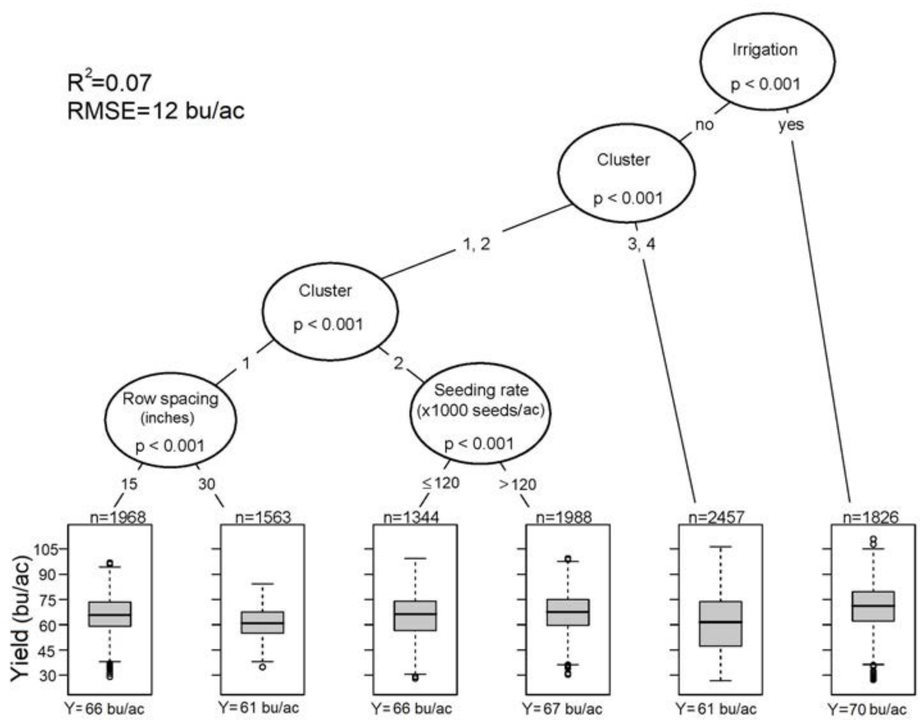
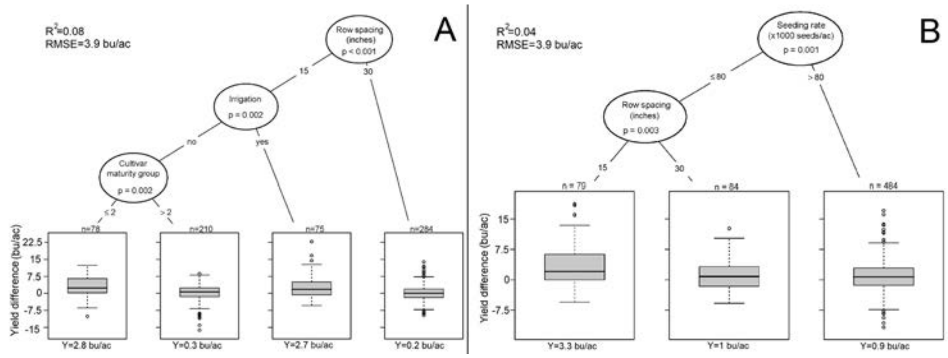


Figure 4. Conditional inference tree for soybean yields (bu/ac) as affected by environment (clusters) and management practices. In each boxplot, the central rectangle spans the first to the third yield quartiles. The solid line inside the rectangle is the mean which is also numerically shown at the bottom (Y). The number of data points comprising each mean is shown on top of each boxplot (n). The white circles show outlier yields.

Figure 5. Conditional inference trees for A) yield difference between fungicide + insecticide- vs. fungicide-treated soybean yields (bu/ac), and B) yield difference between fungicide + insecticide-treated vs. untreated soybean yields (bu/ac) as affected by environment (clusters) and management practices. In each boxplot, the central rectangle spans the first to the third yield quartiles. The solid line inside the rectangle is the mean which is also numerically shown at the bottom (Y). The number of yields is shown on top of each boxplot (n). The white circles show outlier yields.

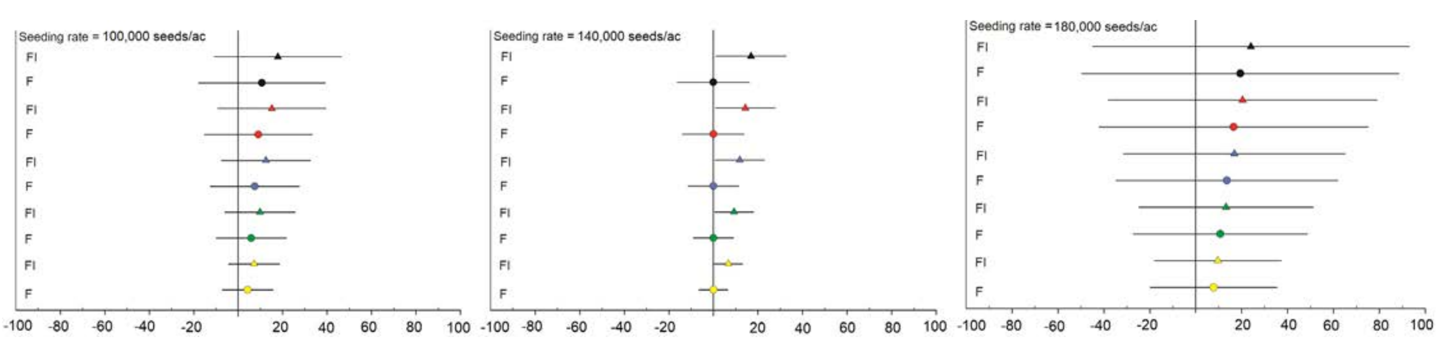


Effectiveness of concurrent use of FST+NST compared to the UTC was mainly affected by row spacing and seeding rate (Fig. 5 B). The yield benefit in these cropping systems reached 3.3 bu/ac. It appears that seed treatments including both FST+NST may be more effective in non-irrigated production systems that use narrow rows, measuring 15 inches. Across the Midwestern and North-central US, prevalent row spacings in non-irrigated production systems are 15 inches (Mourtzinis et al., 2018). Our analysis demonstrates that the optimal management practices are already applied in farmer's fields, and thus, no additional economic yield benefit should be expected from FST+NST applications.

Planting date within a region has a large effect on soybean seed yield (Mourtzinis et al., 2018). Planting date (early vs. late) has also been reported as a risk factor for pest infestation in various crops and US regions. Early planting in cold and wet soil can increase the risk for pest infestation and yield reduction (Hesler et al., 2018). In early and medium planted trials concurrent FST+NST use resulted in 0.9 and 1.5 bu/ac greater yield than UTC seeds, respectively, whereas no yield benefit was observed in late planted fields across the entire region. When repeating the analysis by cluster × planting window, in only half of the early and one fourth of the medium planted clusters FST+NST use resulted in greater yield (between 1 to 1.8 bu/ac) than UTC seeds.

The results in our study show an environmental- and management-specific soybean seed yield response due to the use of neonicotinoid seed treatments. In general terms, these small yield benefits call into question the economic return on investment of prophylactic applications of neonicotinoid seed treatments. Partial economic analysis of the observed yield increases under 8, 11, 14, 17, and 20 \$/bu soybean price scenarios at 100,000, 140,000 and 180,000 seeds/ac seeding rates showed that both FST and FST+NST seed should not cost more than UTC seed (Fig. 6). For all price scenarios, breakeven cost of FST+NST was significant only at 140,000 seeds/ac ($P = 0.034$). Hypothetically, a higher treatment cost would be justified if soybean prices were greater than 20 \$/bu. However, this is extremely unlikely; the average monthly soybean price during the last 10 years was 13 \$/bu and the maximum price has never reached this threshold (maximum of ~19 \$/bu in Aug 2012, a year when drought impacted many states in the soybean-growing region).

Figure 6. Breakeven cost of fungicide only (F - circles), fungicide + insecticide (FI - triangles) seeds compared to untreated (line at 0 \$/a) for 8 \$/bu (yellow), 11 \$/bu (green), 14 \$/bu (blue), 17 \$/bu (red), and 20 \$/bu (black) soybean price scenarios. The lines extend to the lower and upper 95% confidence limits of each income difference (FST=fungicide – untreated and FST+NST=fungicide + insecticide – untreated seed).



The lack of consistent economic yield benefits attributable to NST, coupled with mounting reports of potential environmental risks, highlight that the current default approach of prophylactic applications of NST in soybeans in the US should be re-evaluated. Adjusting other soybean management practices, such as planting date, row spacing and seeding rate, appear to have a greater potential to increase soybean yields across the entire examined region compared to neonicotinoid use (Edreira et al., 2017; Mourtzinis et al., 2018). Such practices represent a net-zero environmental burden compared with the prophylactic use of neonicotinoid treated seeds. IPM, a decision-making process based on scientific data to identify and reduce both yield limiting risks from pests and from pest-management related strategies, can be followed as an alternative to some extent (i.e. soybean aphid). Although sporadic yield-limiting pests are difficult to predict in advance, our data demonstrate that yield-limiting populations of these pests are uncommon across our growing region and that current use rates of NST are likely to far outpace their utility for soybean pest management. This observation is supported by previous analyses (Myers & Hill, 2014), and by recent reviews of the prevalence and population dynamics of soybean insect pests across the region (Hesler et al., 2018).

In response to heightened concerns about the non-target effects of NST use in annual crops, the European Commission restricted the use of clothianidin, imidacloprid and thiamethoxam neonicotinoid insecticides. Initially a moratorium, these restrictions were renewed in 2018 and expanded to a complete ban on all outdoor uses of the compounds in 2018 (Europa, 2018). The restriction in neonicotinoids initially resulted in the use of alternative insecticide seed treatments or foliar applications by farmers (Kathage et al., 2018). Thus, an important issue is the anticipated response of farmers to a similar use restriction in the US. Such action may lead to increased use of alternative treatments and products which in turn, can result in different environmental issues. These applications may be driven more out of a perceived need than actual pest data. Our data provide some measure of security for soybean producers and other agricultural professionals that pest pressure is low across the key soybean-growing regions of the US. In the absence of economically damaging pest populations, insecticides will lead to economic losses. Our study reinforces this point with empirical data for researchers, regulators, and seed sales staff to inform producers about the likelihood of measurable pest management and yield benefits associated with NST use, and we can infer that other, similar pest management approaches would be equally unnecessary in the absence of pests. This affords the industry an opportunity for a correction where NST use rates (and those of other insecticides, current and future) align more closely with pest incidence and risk factors. Given the demonstrable non-target issues associated with the current approach to NST use, we argue that this correction is not only advisable, but necessary if these pest management tools are to be preserved for occasions and cropping systems where they can provide benefit.

Conclusions

Our analysis, spanning 12 years and 14 soybean-producing states, provides no empirical support for continuing the current approach of blanket NST use in soybeans. On the contrary, our data suggest that this approach provides little to zero net benefit in most cases, and that meaningful gains are likely to be realized by site-specific management practices, independent of NST use. Although we do not have site-specific pest data to identify the mechanisms behind our lack of observed pest management benefits, our results are given context by historical data that reflect the scarcity of soybean pests targeted by this approach. This means that throughout most soybean-producing regions of the US, the period of pest protection provided by NSTs seldom aligns with economically significant pest populations. Absent economic infestations of pests, there is no opportunity for this plant protection strategy to provide benefit to most producers.

Adapted from: Spyridon Mourtzinis, Christian H. Krupke, Paul D. Esker, Adam Varenhorst, Nicholas J. Arneson, Carl A. Bradley, Adam M. Byrne, Martin I. Chilvers, Loren J. Giesler, Ames Herbert, Yuba R. Kandel, Maciej J. Kazula, Catherine Hunt, Laura E. Lindsey, Sean Malone, Daren S. Mueller, Seth Naeve, Emerson Nafziger, Dominic D. Reisig, Jeremy Ross, Devon R. Rossman, Sally Taylor, and Shawn P. Conley. 2019. *Neonicotinoid seed treatments for soybean provide negligible benefits to US farmers*. Scientific Reports. https://rdcu.be/bQE3f

References

Chagnon M. et al. *Risks of large-scale use of systemic insecticides to ecosystem functioning and services*. Environ. Sci. Pollut. Res. 22, 119–134 (2015).

Douglas, M.R. et al. *Neonicotinoid insecticide travels through a soil food chain, disrupting biological control of non-target pests and decreasing soya bean yield*. Journal of Applied Ecology. 52: 250-260 (2014).

Douglas, M.R. & Tooker J.F. *Large-scale deployment of seed treatments has driven rapid increase in the use of neonicotinoid insecticides and preemptive pest management in US field crops.* Environ. Sci. Technol. 49: 5088-5097 (2015).

Edreira, R.J.I., et al. *Assessing causes of yield gaps in agricultural areas with diversity in climate and soils*. Agr. For. Meteorol. 247:170-180. (2017).

Europa. Policies, information and services – Pesticides (2018) (accessed at: https://ec.europa.eu/food/plant/pesticides_en)

Fernandez-Cornejo, J., et al. *Pesticide use in US agriculture: 21 selected crops, 1960–2008*. Economic Information Bulletin 124 (2014). USDA Economic Research Service, Washington, DC.

Gaspar, A.P, Marburger D.A., Mourtzinis S. & Conley S.P. *Soybean seed yield response to multiple seed treatment components across diverse environments.* Agron. J. 106:1955-1962 (2014).

Hesler, S.L., Allen, C.K., Luttrell, R.G., Sappington, T.W., & Papiernik, S.K. *Early-season pests of soybean in the United States and factors that affect their risk of infestation.* Journal of Integrated Pest Management. Volume 9, Issue 1, 19 (2018). https://doi.org/10.1093/jipm/pmx028

Hoshi N. et al. *Insight into the mechanism of reproductive dysfunction caused by neonicotinoid pesticides.* Biol. Pharm. Bull. 37, 1439–1443 (2014).

Kathage, J., Castanera, P., Alonso-Prados, J.L., Gomez-Barbero, M., & Rodriguez-Cerezo, E. *The impact of restrictions on neonicotinoid and fipronil insecticides on pest management in maize, oilseed rape and sunflower in eight European Union regions*. Pest Manag. Sci. 74: 88–99 (2018).

Krupke, C. H. et al. *Assessing the value and pest management window provided by neonicotinoid seed treatments for management of soybean aphid (Aphis glycines Matsumura) in the Upper Midwestern United States*. Pest. Manag. Sci, 73: 2184-2193 (2017). doi:10.1002/ps.4602

Lewis, W. J., van Lenteren, J. C., Phatak, S.C., & Tumlinson, J. H. *A total system approach to sustainable pest management.* Proceedings of the National Academy of Sciences, 94 (23) 12243-12248 (1997). doi: 10.1073/pnas.94.23.12243.

Mourtzinis, S., et al. *Sifting and winnowing: analysis of farmer field data for soybean in the US North-Central region*. Field Crops Research 221:130-141. (2018).

Myers, C.M. & Hill E. *Benefits of neonicotinoid seed treatments to soybean production*. United States Environmental Protection Agency: The Biological and Economic Analysis Division. (2014).

Papiernik, S.K., Sappington, T.W. Luttrell, R.G., Hesler, L.S., & Allen, K.C. *Overview: Risk Factors and Historic Levels of Pressure From Insect Pests of Seedling Corn, Cotton, Soybean, and Wheat in the United States*. Journal of Integrated Pest Management, Volume 9, Issue 1, 1, 18 (2018). https://doi.org/10.1093/jipm/pmx026

Pecenka, J.R., & Lundgren, J.G. *Non-target effects of clothianidin on monarch butterflies*. Sci. Nat. 102, 1–4 (2015). doi:10.1007/s00114-015-1270-y

Pisa L.W. et al. *Effects of neonicotinoids and fipronil on non-target invertebrates*. Environ. Sci. Pollut. Res. 22, 68–102 (2015).

Sánchez-Bayo F. et al. *Are bee diseases linked to pesticides? - A brief review*. Environ. Int. 89-90, 7–11 (2016).

USGS. Estimated Annual Agricultural Pesticide Use (2014). (accessed at: https://water.usgs.gov/nawqa/pnsp/usage/maps/show_map.php?year=2014&map=THIAMETHOXAM&hilo=L.)

Woodcock B.A. et al. *Impacts of neonicotinoid use on long-term population changes in wild bees in England.* Nat. Commun. 7, 12459 (2016).