Developing an injury severity to yield loss relationship for soybean gall midge

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Developing an injury severity to yield loss relationship for soybean gall midge

by

Mitchell Lee Helton

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Entomology

Program of Study Committee:
Erin W. Hodgson, Major Professor
Matthew O’Neal
Craig Abel

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2021

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DEDICATION

This thesis is dedicated to my parents, Christopher and Karen Helton, who provided me with endless love and encouragement throughout my life. Your support, guidance, and sacrifices allowed me to pursue any path I wanted. You instilled values of hard work, compassion, respect, and taught me what it means to be a good person. I wouldn’t be the man I am, or have accomplished what I have without the two of you. Everything I am and all I have, I owe to the both of you. Above all, you have been amazing role models and my foundation in life. It’s impossible to ever express my full gratitude, but I’ll start just by saying thank you for being my parents. I love you both.

I am also dedicating this thesis to the rest of my family and friends. I have always been blessed with your unlimited support, and you all have always been there as an avenue to escape the stresses of everyday life. The fun, laughter, and enjoyment I receive from spending time with all of the phenomenal (and one of a kind) family and friends I have, is the greatest aspect of my life. Thank you all for simply being yourselves. You know who you are.
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I would like to thank and acknowledge my committee members, Drs. Matthew O’Neal and Craig Abel, for their contributions to my research and studies. I valued your professional insights, along the questions you offered, which forced me to think more critically and in depth about my research.

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ABSTRACT

Soybean gall midge, *Resseliella maxima* Gagné (Diptera: Cecidomyiidae), is a new pest recently confirmed on soybean, *Glycine max* (L.) Merr. (Fabales: Fabaceae). Found only in Nebraska, Iowa, South Dakota, Minnesota, and Missouri, soybean gall midge infestations have caused severe economic loss to commercial fields beginning in 2018. Much is still unknown about this pest, so our research efforts have been focused on understanding applied biology and management. We developed an injury rating system to quantify the severity of plant injury from soybean gall midge larvae. Research plots from 2019 and 2020 in Iowa and Nebraska were evaluated for injury throughout the growing season and yield was measured. Our objective was to describe the relationship between injury severity and yield loss caused from soybean gall midge. A nonlinear regression model was developed to validate our injury rating system and to express the relationship between season long injury severity and yield loss. Results from our analysis indicate the injury rating system developed correlates well with yield loss caused by larvae and may be an important tool for understanding the economic impact of this emergent pest of soybean.
CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

Thesis Organization

This thesis consists of two chapters. The first chapter is a review of pertinent literature that summarizes the history of soybean production in the United States, soybean gall midge description and background, and the needs for studying this new pest. The second chapter describes our research efforts in the development of a nonlinear regression model which describes the relationship between injury severity and yield loss caused by soybean gall midge.

Literature Review

Soybean production

Soybean, Glycine max (L.) Merr. (Fabales: Fabaceae), is a legume grown for its protein and oil-rich seed with numerous end uses. Soybean was first introduced in the United States by Samuel Bowen in 1765 (Hymowitz and Shurtleff 2005). Large-scale production of soybeans in the United States did not begin until the 20th century, but area planted to soybeans has since increased substantially, mostly credited to agronomic improvements and low production costs (USDA-ERS 2020). Currently, soybean is the second largest cropping system in the nation with over 33 million hectares planted in 2020 (USDA-NASS 2020).

Soybean growth

Soybean is a short-day plant, meaning growth and development is sensitive to photoperiod. It was once thought plants would not flower until after the summer solstice on 21 June, but with the implementation of earlier planting, flowering can occur earlier. Floral induction occurs when soybean leaves can measure night length; thus, when planted early
enough, soybean flowering can begin prior to 21 June (Conley et al. 2019). Soybean cultivars are
categorized into maturity groups, defining where cultivars are best adapted for growing,
primarily based on photoperiod (Scott and Aldrich 1983, Cober et al. 1996). Cultivars belonging
to maturity groups 0 to IV are best adapted for growing in the midwestern United States.

Vegetative (V) and reproductive (R) soybean growth stage determination requires
identification of plant nodes. A soybean plant’s vegetative stage is determined by the number of
fully-developed trifoliate leaves. A soybean plant is considered vegetative growth stage VE
when the cotyledon has emerged from the soil surface, and VC when unifoliate leaves are fully
developed (Licht 2014). Nodes above the unifoliate node consist of trifoliate leaves, and
vegetative development V1 begins with the first trifoliate leaves unfolding (Licht 2014).
Vegetative stages continue with unfolding of trifoliate leaves to Vn, depending on the final
number of trifoliates, which can vary based on the soybean variety and environmental factors
(Licht 2014). Reproductive stages R1 to R8 are determined by flowering, pod development, seed
development, and plant maturity (Fehr and Caviness 1977, Licht 2014).

Yield

Soybean yields steadily increased in the United States at an average annual rate of 23.3
kg/ha/year from 1924 to 2012 (Specht et al. 2014). More recently, yields increased at an even
higher rate, as USDA data showed an increase of 44 kg/ha/year from 2001 to 2010 (Ainsworth et
al. 2012). Unlike maize, Zea mays (L.) Merr., soybean yields show no evidence of reaching a
improvements are largely credited with the continuing yield gains. Through intensive selection
programs, soybean breeders have genetically improved yields by developing herbicide tolerant
cultivars, increasing photosynthetic rates and seed number per plant, and decreasing leaf area
index and plant height (Ainsworth et al. 2012). Specht et al. (2014) estimated that two-thirds of the on-farm yield improvements are likely because of the continual release of higher yielding cultivars and their adoption by soybean producers.

Advancements in agronomic practices have continually been developed during the last century of soybean production and likely account for one-third of on-farm yield gains (Specht et al. 2014). Because agronomic progress is often periodic, correlating yield increase to a specific practice is difficult, but perhaps the most important change has been earlier planting of soybeans. Studies have shown soybean planting dates occurring earlier by an average of 0.49 days/year from 1981 to 2005 in 13 states (accounting for 81% of the national area harvested) (Sacks and Kucharik 2011). Earlier planting results in a longer reproductive growing season, which ultimately can result in an increase in the number of nodes on the main stem (Wilcox and Frankenberger 1987), flowers, pods, and seeds (Pedersen and Lauer 2004). Producers planting soybeans after 1 May can expect to see a yield reduction by 17 to 42 kg/ha/day (Bastidas et al. 2008). Thus, producers planting soybeans on 15 May compared to 1 May, could see a total yield loss of 255 to 630 kg/ha.

Because of the adoption of early planting of soybeans, the use of fungicide seed treatments has increased. Munkvold (2009) reported less than 8% of soybeans planted in 1996 had a seed treatment, compared to more than 30% in 2008. Cool and wet soils, which are more typical for late April and early May, increases the likelihood of seedling exposure to fungal pathogens (Grau and Gaska 2002). Data from studies in Illinois showed fungicide-treated seed resulted in greater plant population and higher yields for early-planted soybeans (Grau and Gaska 2002).
Additionally, soybean producers have the ability to increase yields through other agronomic management tactics. Narrowing row spacing from 76 to 38 cm increased yields, with an average advantage of 248 kg/ha being observed in Iowa (De Bruin and Pederson 2008, Andrade et al. 2019). Incorporating crop rotation with maize raised soybeans yields by 8% and adopting a no-tillage system increased yields by 6.1% (Pederson and Lauer 2003). Increasing other production inputs, such as fertilizers, pesticides, seed treatments, and seeding rates can increase soybean yields, but may not be economically feasible based on production costs and environmental factors (Greer et al. 2020).

Insect pests

Prior to the rapid expansion of soybean production in the 1960’s, insects were not often recognized as pests of soybean, with the exception being in Asia (Turnipseed 1973). As the area of soybean production has increased, insect pests have become more prevalent. To name a few, insect pests of soybean in the United States include bean leaf beetle, *Ceratoma trifurcata*; armyworms, *Spodoptera* spp.; cutworms, *Argotis* spp.; velvetbean caterpillar, *Anticarsia gemmatalis*; Mexican bean beetle, *Epilachna varivestis*; southern green stink bug, *Nezara viridula*; and most important in the midwestern United States, soybean aphid, *Aphis glycines* (Ragsdale et al. 2004, O’Neal and Johnson 2010).

Prior to 1968, the soybean stem feeding niche was unclaimed in the United States, until soybean stem borer, *Dectes texanus*, was first recognized as a pest of soybean in Missouri and North Carolina (Daughtery and Jackson 1969, Falter 1969). *Dectes texanus* larvae enter soybeans through the petiole, tunneling and feeding on the pith inside the plant stem, often causing lodging (Hatchett et al. 1975). Since its initial discovery, *D. texanus* has been documented in nearly all soybean producing states in the United States (Buschman and Sloderbeck 2010). Soybean stem
fly, *Melanagromyza sojae*, is another significant stem feeding soybean pest. *Melanagromyza sojae* has a wide distribution with confirmed documentations in Asia (Van Den Berg 1998, Wang and Gai 2001, Thapa 2012), Europe (Gil-Ortiz et al. 2010, Strakhova et al. 2013), North East Africa (Abdallah et al. 2014), Australia (Brier and Charleston 2013), and most recently South America (Arnemann et al. 2016, Guedes et al. 2017, Arnemann et al. 2019). The eggs of *M. sojae* are oviposited on the underside of young leaves, and once hatched the larvae mine through the leaf tissue and petiole, into the stem, where they feed on the pith (Brier and Charleston 2013). Larvae indirectly, and briefly, feed on the xylem and phloem of the stem by creating an exit hole for the adult to exit after pupation inside the stem is finished (Brier and Charleston 2013).

Insecticides are the traditional tool used to protect soybean yield from insect pests, but were rarely used prior to the discovery of soybean aphid in the United States. In 2000, less than 0.1% of soybean acreage was treated with insecticide (Ragsdale et al. 2011), while in 2018 the total acreage jumped to 16% (USDA-NASS 2019). While insecticides are typically used in the presence of economic threshold populations, results from Orlowski et al. (2016) displayed soybean yields increased when applying foliar insecticides, regardless of insect pest pressure. Nevertheless, growers should be hesitant to apply treatments in the absence of economic thresholds, as with repeated uses, insects can develop resistance to the active ingredients and modes of action in insecticides (Elzen and Hardee 2003, Ragsdale et al. 2007, Bielza 2008).

**Soybean gall midge**

Soybean gall midge, *Resseliella maxima* Gagné (Diptera: Cecidomyiidae), is a new pest of soybean in Nebraska, Iowa, South Dakota, Minnesota, and Missouri (Gagné et al. 2019, McMachan et al. 2021). Soybean gall midge larvae feed on the stems of soybeans near the base
of the plant, with the heaviest concentrations of infestations occurring at the field edge, dissipation towards the field interior (Gagné et al. 2019). Injury from soybean gall midge was first reported in 2011 in Nebraska, 2015 in South Dakota, and 2016 in Iowa (Hodgson 2018, McMechan et al. 2021). Globally, soybean gall midge is not known to occur elsewhere.

Description

The genus *Resseliella* has 56 known species with relatively uniform morphology (Gagné et al. 2019). The description of characteristics defining *R. maxima* are listed here. Soybean gall midge adults ([Figure 1.1](#)) have an orange abdomen; and long, slender legs with alternating dark and light bands. Females typically are larger than males. Wings are mottled with yellow and black scales and are approximately 2.0 to 2.1 mm in males and 2.3 to 2.5 mm in females (Gagné et al. 2019). Antennae are beaded with alternating color of dark and light bands (Gagné et al. 2019). Foreclaws contain two basal teeth (a characteristic shared with only one other *Resseliella* spp.), while both mid- and hindclaws are untoothed (Gagné et al. 2019). Larvae ([Figure 1.2](#)) are spindle form and legless, orange at third instar (Gagné et al. 2019), and pale, white or translucent at first and second instars. Currently, there is no literature describing the pupal stage of soybean gall midge.

Life cycle

Research efforts are still being made to fully understand soybean gall midge biology and life cycle. Nonetheless, the life cycles of similar species in Cecidomyiidae and *Resseliella* will be discussed. Cecidomyiid adults are short-lived, with most likely surviving less than two days, or long enough to mate and deposit eggs (Gagné 1989). The emergence of other adult midges in *Resseliella* has been found to depend on weather and temperature (Pitcher 1952). There is some
debate regarding emergence in correlation with time of day for gall midges. For *Resseliella theobaldi*, a pest of raspberry (*Rubus idaeus*), Pitcher (1952) proposes emergence occurs evenly during the day, while Barnes (1944) states emergence occurs in the evening. Gagné (1989) suggests that cecidomyiids typically emerge at dusk or dawn when humidity levels are higher. Regardless of emergence related to the time of day, cecidomyiids must synchronize their emergence that best matches with their host’s biology (Gagné 1989). Between sexes, males commonly emerge first and remain near the location, waiting for female emergence (Gagné 1989). Reports from Iowa and Nebraska suggest that adult soybean gall midge first emergence begins in early to mid-June (Hodgson et al. 2020, McMechan et al. 2020). Observations from infested states also show that the first flight of adults emerge from fields planted in soybeans the previous year (Potter and Koch 2019, Hodgson et al. 2020, McMechan et al. 2019a, Varenhorst 2020). This would support the hypothesis that soybean gall midge overwinters in the same field where feeding occurs.

Soybean gall midge adults have been observed under greenhouse conditions laying eggs in the stem’s small cracks, or fissures, below the cotyledonary node (McMechan et al. 2021).
Species similar to soybean gall midge oviposit eggs on plant surfaces, in-plant crevices, or directly into plant tissue (Gagné 1989, Gordon and Williamson 1991). Pitcher (1952) found evidence that R. theobaldi preferred fresh splits in raspberry primocanes over older, already infested splits.

The life cycle of cecidomyiid larva is highly variable. The larval stage may last less than two weeks to more than two years, although the long-living larva spends much of their life cycle in diapause (Gagné 1989). Currently, no evidence exists supporting that soybean gall midge larvae enter diapause. Cecidomyiid larvae have piercing-sucking mouthparts and feed on a liquid diet of plant, which are broken down by salivary secretions (Gagné 1989, Gagné et al. 2019). Mature larvae of many similar species drop to the soil, spin cocoons, and pupate in the upper layer of the soil (Gagné 1989, Gordon and Williamson 1991). The number of days spent in the cocoon varies; thus this portion of the soybean gall midge life cycle is still unclear.

The number of generations per year for soybean gall midge, and similar species, is difficult to distinguish because of continuous emergence and overlapping generations. Studies done on R. theobaldi observed three generations of adult flight in Norway, Russia, and Sweden, four generations in central Europe, and possibly five generations in Italy (Cross et al. 2008). Also, on R. theobaldi, three generations per year were observed in Poland (Łabanowska and Cross 2008), the United Kingdom (Pitcher 1952), and the Netherlands (Nijveldt 1963). Observations in infested states in the United States, have shown flights of at least two generations of soybean gall midge, and possibly a third, with likely overlapping generations (McMechan et al. 2019a, Hodgson et al. 2020).
Plant injury

Larvae feed on plant tissues near the base of the soybean stem, disrupting nutrient, and water movement within the plant (Dean et al. 2020). Infested plants often display dark markings on the stem resulting from larval feeding. Shortly after infestation plants will often wilt, stems will become brittle and potentially snap off at the feeding site, resulting in total yield loss. Infested plant stems have also been discovered with galls (swollen plant tissue) formed near the feeding site (Dean et al. 2020). Larval feeding is typically restricted to the xylem and phloem tissues at the base of the stem.

Soybean gall midge infestations typically begin and are most severe, at the field edge, with infestations decreasing towards the center of the field (McMechan et al. 2021). Pressure from soybean gall midge can vary between locations and years, thus injury severity can also differ significantly. It is worth noting that soybean gall midge larval feeding has caused yield losses of up to 100% on field edges (Potter and Koch 2020, McMechan et al. 2021). At the time of this writing, there are no research-based management strategies to protect yield from soybean gall midge infestations. Due to continual emergence and multiple generations, plants are subjected to season long exposure to soybean gall midge feeding. Currently there is no literature which describes how to measure a plant’s season-long exposure to soybean gall midge, but methods have been used in other plant and insect systems. Van der Plank (1963) suggested the use of an area under the disease progress curve to assess crop exposure to a persistent biotic stressor. This method has been widely adopted by plant pathologists to describe disease intensity over time (Jeger and Viljanen-Rollinson 2001). Entomologists have utilized this concept, most notably to describe season-long crop exposure to aphids (Hanafi et al. 1989, Ragsdale et al. 2007). Similar methods may be appropriate to describe the season-long crop exposure to soybean
gall midge feeding, and may provide a better understanding of the relationship between injury and yield loss.

References


CHAPTER 2. DEVELOPING AN INJURY SEVERITY TO YIELD LOSS RELATIONSHIP FOR SOYBEAN GALL MIDGE

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Modified from a manuscript to be submitted in the *Journal of Economic Entomology*

Abstract

Soybean gall midge, *Resseliella maxima* Gagné (Diptera: Cecidomyiidae), is a new pest recently confirmed on soybean, *Glycine max* (L.) Merr. (Fabales: Fabaceae). Found only in Nebraska, Iowa, South Dakota, Minnesota, and Missouri, soybean gall midge has caused severe economic loss to commercial fields beginning in 2018. Much is still unknown about this pest, so our research efforts have been focused on biology and management. We developed an injury rating system to quantify the severity of plant injury from soybean gall midge larvae. Research plots from 2019 and 2020 in Iowa and Nebraska were evaluated for injury throughout the growing season and yield was measured. Our objective was to describe the relationship between injury severity and yield loss caused from soybean gall midge. A nonlinear regression model was developed to validate our injury rating system and to express the relationship between season long injury severity and yield loss. Results from our analysis indicate the injury rating system we developed correlates well with yield loss caused by larvae and may be an important tool for understanding the economic impact of this emergent pest of soybeans.

Introduction

Soybean, *Glycine max* (L.) Merr. (Fabales: Fabaceae), is the second most economically important crop in the United States, with over 33 million hectares planted in 2020 (USDA-NASS
Recently, the soybean crop in some Midwestern states has been threatened by a new insect species. Soybean gall midge, *Resseliella maxima* Gagné (Diptera: Cecidomyiidae), is a new pest of soybean found in Nebraska, Iowa, South Dakota, Minnesota, and Missouri (Gagné et al. 2019, McMechan et al. 2021).

Soybean gall midge larvae feed on tissue near the base of the plant (Gagné et al. 2019). Feeding injury disrupts nutrient and water movement (Dean et al. 2020) causing plants to wilt and potentially snap off at the feeding site. Larval infestations are typically heaviest at the field edge, with infestation levels dissipating towards the center of the field (McMechan et al. 2021). Soybean gall midge larval feeding may cause up to 100% yield loss on field edges (McMechan et al. 2021).

Due to continuous adult emergence and multiple generations (McMechan et al. 2019, Hodgson and Helton 2021), plants are subject to season-long exposure to soybean gall midge feeding. Spatially, soybean gall midge infestations result in highly variable amounts of plant injury. Thus, the relationship between injury severity and overall yield loss from soybean gall midge infestations is not fully understood. The objective of this research is to create a model representing the relationship between the level of injury severity from soybean gall midge larval feeding and the yield loss it caused. To achieve this objective, experimental field plots were monitored throughout multiple growing seasons for injury caused by soybean gall midge infestations. Injury severity ratings and final yield measurements were used as data inputs to express the relationship between injury severity and yield loss.
Materials and Methods

Data collection and plot establishment

Data for this project were collected from small-plot research trials in Iowa and Nebraska from 2019 and 2020. The trials were conducted on both university research farms and commercial farms located in Cass and O’Brien Counties in Iowa, and Cass, Lancaster, and Saunders Counties in Nebraska. To increase the likelihood of infestations, all trials were planted along field edges at locations where soybean gall midge injury had been observed in previous years. Preceding crops were soybean or maize, *Zea mays* L. (Poales: Poaceae), with adjacent fields planted in soybean. We collected data from 11 research trials, all of which were a variety of insecticide efficacy evaluations. In Iowa, soybean plots were planted at four rows wide, 9.14 m long, with 76.2 cm row spacing, and at a population of 345,947 seeds ha\(^{-1}\). In Nebraska, soybean plots were planted at four rows wide, 9.14 m long, with 76.2 cm row spacing, and at populations of 365,674 seeds ha\(^{-1}\), 373,129 seeds ha\(^{-1}\), and 396,141 seeds ha\(^{-1}\). Planting dates ranged from 23 April to 12 May. Multiple varieties were used, with maturity group ranging from 2.4 to 3.2 in Iowa and 2.7 to 3.2 in Nebraska. A summary of information for the trials used in this analysis can be found in Table 2.1. Some trials received pesticide applications - herbicides were used to minimize the impact of weeds, and various seed-applied, foliar, and in-furrow insecticide treatments were included in trials focused on efficacy evaluations.

To measure plots for injury severity from soybean gall midge larval feeding, we developed a visual rating system. Soybean gall midge larvae are small in size, 0.5 to 3.0 mm long, and also feed within the plant stem (Gagné et al. 2019). Therefore, assessing plant injury based on larval abundance would require destructive sampling and would be difficult to quantify accurately, especially in the field. For these reasons, visually rating plots was determined to be the most efficient method for evaluating injury levels. All plots were evaluated for injury
throughout the growing season and were rated on a 5-point scale, which ranges from 0 to 4 depending on the percentage of plants showing visual injury symptoms (wilting, lodged, or dead) caused by soybean gall midge infestations. Individual injury rating values with the related approximate percentage of total injured plants (±12.5%) is described as: 0 = 0%, 1 = 25%, 2 = 50%, 3 = 75%, and 4 = 100%. The linearity of the injury rating system allows users to further break down the ratings for greater precision. In some instances, we incorporated ratings in increments of 0.25 to document relatively small differences between plots. Figure 2.1 provides photographic examples of the various injury rating levels used to evaluate soybean gall midge feeding. All plots were given a weekly injury rating until plant senescence began.

Plots were harvested with an ALMACO (Nevada, IA) SPC40 combine. Yields were determined by weighing grain with a hopper which rested on a digital scale sensor custom-designed for each combine. Yields were corrected to 13% moisture and reported in kilograms per hectare.

Figure 2.1. Representative photographs depicting the various rating levels used to assess soybean gall midge feeding severity: a) 0 or 1, (b) 2, (c) 3, and (d) 4. Each photograph was taken from the center front of a four-row plot 9.14 m in length. Distinct photographs for ratings of 0 and 1 were not provided because these plots often appear similar from this vantage point and require closer examination of the plants within the plot to assign a value.
Table 2.1. Summary of trials included in analysis.

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**Data transformation**

A method for assessing crop exposure to a persistent biotic stressor was suggested by Van der Plank (1963) in the form of an area under the disease progress curve. This method has been adopted widely by plant pathologists to express disease intensity over time (Jeger and Viljanen-Rollinson 2001). The concept has been used by entomologists as well, most notably to describe season-long crop exposure to aphids (e.g., Hanafi et al. 1989, Ragsdale et al. 2007). We adapted this method as an area under the severity progress curve (AUSPC) to quantify season-long exposure to soybean gall midge feeding injury by transforming our discrete injury ratings into a cumulative injury value. First, injury ratings were expressed on a 0 to 100 scale, in which the new value equals the approximate percentage of total plot injury represented by our injury rating system. For example, a 2 on our injury rating scale would be transformed to 50. Next, the average of two sequential transformed values were multiplied by the number of days between the two dates the injury ratings were collected. This number was added to the previous cumulative injury value. This process is repeated for each individual injury rating through the last rating to obtain a final AUSPC value. This technique can be expressed using the formula \[ \text{AUSPC} = \sum_{i=1}^{n} (\bar{x}_{i, i-1} \times d_{i}) \], where \( n \) is the number of sampling dates, \( \bar{x}_{i, i-1} \) is the average transformed injury rating between sequential sampling dates \( i \) and \( i - 1 \), and \( d_{i} \) is the number of days since the previous sampling date.

Plots were established in multiple locations and years. As a result, yield potentials due to different environments had to be normalized across locations and years. To account for variation in yield potential, plot yields were expressed as proportions relative to the maximum possible yield at the location plots were established (Catangui et al. 2009). Maximum yield was determined by utilizing historical yields from previous growing seasons at each location.
Regression analysis

To express the relationship between injury severity and yield loss, a nonlinear logistic decay regression model in the form of 

\[ y_i = \frac{1}{1+e^{(b x_i - a)}} + \varepsilon_i, \]

where \( y_i \) is the proportion of maximum yield associated with observation \( i \), \( x_i \) is the AUSPC value associated with observation \( i \), \( b \) and \( a \) are regression parameters associated with the function’s rate of decay and midpoint, \( e \) is Euler’s number (2.71828), and \( \varepsilon_i \) is the random error term associated with observation \( i \). The error term is assumed to have an independent normal distribution with a mean of 0 and constant variance. The \texttt{nls} function of the \texttt{R} package \texttt{stats} (version 3.6.2) in RStudio (version 1.2.5033) (RStudio, Inc., Boston, MA) was used to determine least-squares parameter estimates for \( b \) and \( a \). Based on visual inspection of the data, initial starting values for estimating parameters were 0.001 (\( b \)) and 2.5 (\( a \)).

Outliers in the data were identified if the standardized residual for a given observation resulting from an initial model fit was greater than or equal to three. Seven outliers were identified and removed from our analysis due to the tendency of outliers to influence a fitted function disproportionately when using the least-squares method (Kutner et al. 2005). Residuals (\( e_i \)) were assessed graphically to determine whether assumptions related to the error term were met. A histogram (Figure 2.2) and quantile plot (Figure 2.3) of standardized residuals confirmed a generally normal distribution with a mean of 0, and a plot of sequential residuals (\( e_{i+1} \) vs. \( e_i \)) indicating the error term was uncorrelated (Figure 2.4). The \texttt{predictNLS} function of the \texttt{R} package \texttt{propagate} (version 1.0-6) was used to estimate 95% confidence and prediction intervals for the model (Figure 2.5). Examination of the distribution of observations about the fitted model in this figure did not reveal a substantial departure from the assumption of constant variance.
Figure 2.2. Histogram of standardized residuals.

Figure 2.3. Quantile plot of standardized residuals.
Figure 2.4. Correlation plot of sequential residuals ($e_{i+1}$ vs. $e_i$).

Figure 2.5. Area under the severity progress curve (AUSPC) model with 95% confidence and prediction intervals.
Results

For this model, a total of 505 observations (excluding outliers) were used to estimate injury severity and associated yield loss. Initial injury severity ratings were collected weekly between 2 July (Nebraska, 2020) and 11 July (Iowa, 2019), and ended between 28 August (Nebraska, 2020) and 10 September (Iowa, 2019). The number of weekly ratings collected varied across locations, ranging from 8 to 10 collection dates per trial. AUSPC values ranged from 0 (Iowa, 2020) to 6,325 (Iowa, 2019) with a mean of 1,731, and yield proportions ranged from 0.00 (Iowa, 2019) to 1.00 (Iowa, 2019 and 2020, and Nebraska, 2020) with a mean of 0.59. Least-squares parameter estimates resulted in $b = 0.0008591$ (standard error = 0.0002293, $t = 37.46$, and $P < 0.0001$) and $a = 1.914$ (standard error = 0.05114, $t = 37.44$, and $P < 0.0001$). The nonlinear regression model is expressed in Figure 2.6.

![Nonlinear LS regression](image)

**Figure 2.6.** Nonlinear regression model representing the relationship between yield proportion and AUSPC.
Discussion

This study is the first to describe the relationship between plant injury severity and yield loss from soybean gall midge. The primary goal was to improve our understanding of the potential injury and yield loss that can occur from season long exposure to soybean gall midge larval infestations. Due to this pest being a new species, understanding the injury potential of soybean gall midge will aid in the development of pest management strategies. This model can be used to predict the potential loss of yield at a given level of injury severity during the season. Predicting the yield loss associated with larval feeding allows for a more complete understanding of the economic impact of this pest and can serve as the foundation for determining whether potential control measures will be economically justifiable.

Another goal of this research was to develop an injury rating system to quantify injury caused by soybean gall midge. The results from our model indicate that our injury rating system is closely associated with observed yield loss and soybean gall midge injury levels. We believe that our injury rating system is a useful tool in assessing and recording plant injury as a result from soybean gall midge larval feeding. Key advantages of the rating system we designed are that the ratings are based on relatively conspicuous signs of feeding injury (wilted, lodged, or dead plants) and that ratings are non-destructive in nature, meaning that repeated, season-long observations can be performed on the same plants used to estimate yield at the end of the growing season.

We hypothesize that the injury severity approach outlined in this project may also be used to describe the relationships of yield loss and insect injury in other pest systems that also produce a drawn out, season-long effect on the crop. The inputs for this project simply rely on injury ratings recorded throughout the duration of injury presence and final yield. With these data
collection methods and analysis, the associated yield loss with an extended feeding period in other insects, with overlapping, multigenerational life cycles, can be better understood.

Potential factors that were not explored in this study may have an impact on the model. While environmental variability in soil characteristics, local weather conditions, and soybean variety were accounted for indirectly by expressing yield loss for each plot as a proportion of an estimated maximum for the trial site, it may be possible that these factors actually play an important role in the likelihood and/or severity of soybean gall midge injury. Further experiments should be conducted to determine which factors may affect the severity yield loss associated with injury caused by this pest. Geographically, our analysis includes only five counties in two states, while soybean gall midge infestations have been confirmed in 114 counties in five states (McMechan et al. 2021). Efforts should be made in the future to include data inputs from a wider geographic region to validate our model. Yet another factor to consider is that all trials included in this project were planted along field edges, where other biotic and abiotic stressors are known to decrease yields (Sara et al. 2013, Nguyen and Nansen 2018, Carlesso et al. 2019). Additional research is needed to better understand the dynamics between field edge stressors, soybean gall midge injury, and yield loss to help identify effective strategies for this pest’s control.

Acknowledgements

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References


CHAPTER 3. GENERAL CONCLUSION

Soybean is the second largest cropping system in the United States, with over 33 million hectares planted in 2020 (USDA-NASS 2020). Although soybeans were first introduced into the United States in 1765 (Hymowitz and Shurtleff 2005), its adoption as a large-scale production crop did not occur until the 20th century (USDA-ERS 2020). Over the past century, yields have increased substantially and soybean production is valued at approximately $46 billion in the United States (USDA-NASS 2020).

Prior to the 1960’s, when soybean production quickly expanded, insects were rarely seen as pests of soybean in the United States (Turnipseed 1973). As soybean acreage increased, insect pests began developing, and today a number of insect pests feed on soybeans. Soybean aphid, *Aphis glycines*, is a phloem feeding insect, and is considered the most economically harmful soybean pest in the midwestern United States. The most common management strategy for protecting soybean yields from insect pests, is the use of insecticides. While not frequently used prior to 2000, insecticides were applied to 16% of the total soybean acreage in 2018 (USDA-NASS 2019).

Recently soybean gall midge, *Resseliella maxima* Gagné, was identified as a new pest of soybean in Nebraska, Iowa, South Dakota, Minnesota, and Missouri (Gagné et al. 2019, McMeechan et al. 2021). Soybean gall midge larvae, feed on soybean stems near the base of the plant (Gagné et al. 2019). Larval infestations and yield losses are typically heaviest at the field edge, and dissipate towards the field interior (McMeechan et al. 2021). Soybean gall midge observations have shown continuous adult emergence with multiple overlapping generations, which results in season-long exposure to larval feeding (McMeechan et al. 2019, Hodgson and Helton 2021).
As with any new species, there are still many questions regarding soybean gall midge, including the relationship between injury severity and yield loss from larval infestations. The objective of Chapter 2 was to explore this relationship to better our understanding of potential injury and associated yield loss. Additionally, we also aimed to design a system to measure injury severity from soybean gall midge infestations in the field. We developed a visual rating system that assesses injury severity on a 5-point scale, depending on the percentage of plants showing visual injury symptoms from larval feeding. This injury rating system is linear in nature, and can be broken down further, if greater precision is desired by the user. Another key advantage of this system, is that ratings are non-destructive, allowing for repeated observations throughout the growing season.

To better understand soybean gall midge injury severity and yield loss, we developed a model using a nonlinear logistic decay regression function to describe this relationship. This analysis is the first to describe the relationship between plant injury severity and yield loss from soybean gall midge, and improves our understanding of the economic impact of this new pest. With this model we can predict the potential yield loss associated with a given level of injury severity, which can aid in developing pest management strategies for soybean gall midge. The results from our model also indicate that our injury rating system is closely associated with yield loss and soybean gall midge injury levels. We believe this injury rating system will be a useful tool for others studying soybean gall midge.

We hypothesize that the methods used in the analysis from Chapter 2, could be useful in describing the relationship of injury potential and yield loss for other pests that also produce a season-long toll on the crop. Our inputs in this analysis simply require season-long injury ratings
and final yield. From that data, the yield loss caused by other insects with extended feeding periods and overlapping, multigenerational life cycles, can be described.

More research and efforts are needed to further explore soybean gall midge and its injury potential for a complete understanding. Soil characteristics, weather, and production practices are a few variables that were accounted for in our study, but may play a bigger role in the probability and/or the severity of soybean gall midge infestations. Future efforts should be made to expand this analysis to more variables across a wider geographic region to gain a complete picture of the injury severity to yield loss relationship.

References


