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Weather and Geographic Effects on Sugarcane Aphid Migration

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Sugarcane aphids Melanaphis sacchari (Aphididae: Hemiptera) cause significant economic damage to sorghum production. This study measures the effects of weather, geographic, and biological characteristics of sugarcane aphid (SCA) on the infestation of sorghum fields in Oklahoma. Infestation likelihood curves suggest there is a difference in the infestation probability between the high- and low-density wing/un-winged sugarcane aphid groups. The larger the ratio of winged to un-winged sugarcane aphid, the more likely their movement to other sorghum fields. Proportional hazard regression results affirm that weather is an important factor in determining infestation hazards. This study uses information on field-level infestations of sorghum by sugarcane aphis. Data were collected by scouting sorghum fields for SCA infestation during the 2017 growing season in Oklahoma. Field location, the distance between sampled fields, and the day SCA were observed was recorded. Field location and the distance between sampled fields was not a significant factor affecting the likelihood of field infestation. The total population of sugarcane aphid per plant in the most recently infested field was negatively correlated with infestation hazard. These findings may contribute to development of early warning infestation alarms through the coordination of farm-to-farm pesticide use and harvest timing. Increased investments in real-time pest monitoring including on-farm detection, report transmission, and forecasted movements could improve the accuracy of early warning SCA system for producers, thereby mitigating the negative economic impacts caused by infestation.

Keywords: Geography, precipitation, sorghum, sugarcane aphids, temperature, time-to-infestation.

1. INTRODUCTION

This study measures the effect of weather variables and geographic features on the infestation of Oklahoma sorghum production by Sugarcane aphid (SCA). Weather variables, including temperature, humidity, and precipitation, as well as the growth stage of sorghum, affect the susceptibility of sorghum plants to SCA and their proliferation (Behura & Bohidar, 1983; Mote, 1983). Documentation of the effects of environmental variables, including temperature, moisture, and humidity, on insect life cycles is often performed in controlled laboratory settings. This is the first study to examine the effect of geographic and weather variables on the migration of SCA at the sorghum-field level using a survival model, which is also called a proportional hazard model (PHM). PHM is a flexible, regression-based modeling approach capable of incorporating the effects of weather, location, and temporal covariates for determining the likelihood of field-to-field SCA migration (Cox, 1972).

The study uses field-level observations of SCA infestations on Oklahoma sorghum fields to determine how weather variables and field proximity influence the time until a field is infested. Infestation dynamics and population colonization vary, and depend on factors such as native vegetation, food density, host plant species abundance, timing and rate of migration and dispersal, and geographic location (Singh, Padmaja, & Seetharama, 2004). The study was conducted during the 2017 growing season. Producers and researchers scouted fields on a daily basis for SCA. The date, the proportion of winged versus unwinged SCA, and distances to the most recently infested sorghum field were recorded. The covariates used in the SCA migration regression include distance between sorghum fields, temperature, precipitation, wind direction, and the date when SCA were observed on a given field. Findings may be useful for developing predictive models for SCA migration and the time until a sorghum field is infested.

2. LITERATURE REVIEW

Sugarcane aphid (*Melanaphis sacchari*, Hemiptera: Aphididae) is a pest found in more than 30 countries that feeds on 20 species of rice and other commodity crops (Singh, Padmaja, & Seetharama, 2004). In the United States, sorghum, sweet sorghum, and some millet varieties are SCA's main hosts since its introduction in the 1970s (Singh, Padmaja, & Seetharama, 2004). SCA transmits sugarcane yellow leaf virus, causing yield loss in sorghum (Behary Paray et al., 2011; Gonçalves, 2005; Lopes et al., 1997).

Damage to sorghum caused by SCA depends on factors such as aphid/plant density and the duration of infestation (Singh, Padmaja, & Seetharama, 2004). Weather variables also affect SCA population density, their migration, and survival. Studies measuring the relationship between temperature and SCA population density find that dispersal of aphids occurs within 6 to 10 days at temperatures between 18 and 30°C, with populations destroyed at 35°C (Behura & Bohidar, 1983). SCA thrive and proliferate on sorghum as humidity increases (Mote, 1983). Warm temperatures have a positive effect on aphid populations until a critical temperature of 35°C is reached, while rainfall has a negative effect on SCA survival (Mann et al., 1995). Rainfall also removes aphids from host plants and makes SCA more vulnerable to predators (Cocu et al., 2005; Klueken et al., 2009). SCA infestation of sorghum may be most severe during the late sorghum growth phase due to plant stress caused by drought. SCA colonies increase rapidly after the piping stage (the extrusion of tailpipe-like appendages) (Van Rensburg, 1973). SCA populations on a single plant may reach as much as 30,000 individuals (Setokuchi, 1976).

3. METHODS AND PROCEDURES

3.1 Time-to-Infestation Curves

Time-to-infestation curves depict the probability of a sorghum field becoming infested over some period. There are no previous studies analyzing the relationship between winged and un-winged SCA populations and the likelihood of a field becoming infested. Winged individuals are relatively more resistant to starvation (Noda, 1960), have a longer reproductive period, and live longer (Tsuji & Kawada, 1987; Tsumuki et al., 1990). These factors are hypothesized positively affect the likelihood of migration and field infestation. The expected result is that there will be a difference in the infestation curve according to the winged/un-winged ratios.

The type of infestation (or 'hazard') curves used here require assigning outcomes to discrete groups (Allison, 2010). The winged/un-winged ratio is categorized into a 'High' and 'Low' category based on the median value of 1.4% (the un-winged/winged ratio). For reference, the number of surveyed fields with the number of winged alatae less than 1 was 34 (97.1%), and the number of fields with the number of wingless alatae was 28 (80%). The number of fields with a ratio of 0 was 14 (40%), and the number of fields with a ratio of 0.1 or less was 24 (68.6%).

Regional differences in growing conditions may also accelerate or deter SCA infestation. The southwestern Great Plains region is a direct route for SCA migration from Texas northward. The likelihood a field becomes infested more quickly is expected to be relatively higher in the southwestern region compared to the north-central and northwestern regions of Oklahoma. Thus, time-to-infestation curves are estimated for each region.

Inter-field distance is also expected to influence the likelihood a field is infested by SCA. A time-to-infestation curve is generated for each of the four distance variables. Inter-field distance was classified into 'closer' and 'more distant' fields using the mean values of the distances as an arbitrary cut-off. The fact that SCA (especially winged SCA) migrate over long distances and can cause rapid diffusion (Suarez, Holway, & Case, 2001) supports the assumption that there is a difference in the hazard of infestation according to field proximity.

The mean values of each distance covariate are 207.6 miles (distance between the last infested sorghum field in Texas and all Oklahoma sorghum fields), 116.86 miles (distance between the first sorghum field infested in Oklahoma and to all other fields in Oklahoma), 39.67 miles (distance between the first infested field in a region to other fields in the same region), and 43.76 miles (distance between temporally consecutive infested fields) are used to group observations into 'Low' and 'High' wing classes. The null hypothesis is that the distributions of the infestation curves for each group ('Low' and 'High') are not different.

3.2 Proportional Hazard Model

In addition to the univariate comparisons of time-to-infestation curves, a proportional hazard model (PHM, (Cox, 1972)) is used to determine the *ceteris paribus* effects of covariates on the likelihood of a field being infested by SCA (Allison, 2010). PHM model the likelihood of a hazardous event occurring as a censored outcome (George, Seals, & Aban, 2014). Censoring occurs when an event is unobserved before the study terminates. For the data collection period of this research, the first observation date is the left censoring date, and October 16 the right censoring date. There were 12 right-censored (un-infested) fields observed over the 139 days of data collection. In Oklahoma, sorghum planting occurs between April to July with harvest following in September to November (Hawkins et al., 2004). Infestation can occur on multiple sorghum fields during this period. This means that uninfected fields in the north-central and northwestern regions may be left- or right-censored because SCA migrate south to north. Infestation is also less likely to occur earlier than the left-censoring date of May 31. Therefore, fields where infestation did not occur during the data collection period are right-censored. 34 fields were infested between 31 May and 16 October, and are recorded as interval-censored observations.

The PHM measures the hazard of a field becoming infested by SCA on day t is $h(t) = \lim_{\Delta t \to 0} \frac{Pr(t \le T < t + \Delta t | T \ge t)}{\Delta t}$, where $h(t)$ is the infestation hazard and is a function of time and Δt is an incremental time step measured in days. The PHM assumes the effect of a covariate is multiplicative with respect to the hazard rate. The PHM, including the weather and geographic instruments, is:

$$(1)\qquad h_i(t) = h_0(t) \cdot exp\left(\beta_1 \cdot l_i^p + \beta_2 \cdot l_i^n + \beta_3 \cdot \left(\frac{d_i^1}{100}\right) + \beta_4 \cdot \left(\frac{d_i^2}{100}\right) + \beta_5 \cdot \left(\frac{d_i^3}{100}\right) + \beta_6 \cdot \left(\frac{d_i^4}{100}\right) + \beta_7 \cdot ta_i + \beta_8 \cdot ra_i + \beta_9 \cdot an_i + \beta_{10} \cdot tp_i + \beta_{11} \cdot w_i\right)$$

where $h_0(t)$ is a baseline hazard function; and $\boldsymbol{\beta}$ are parameters to be estimated. The hazard associated with a covariate is a log odds ratio. The ratio is calculated as the exponential of the estimated coefficient. For dummy variables, the log odds are interpreted as the ratio of the hazard for a variable with a value of '1' to the hazard for a variable with a value of '0'. That is, the hazard ratio is the difference in the likelihood of becoming infested (Motulsky, 2014). For continuous covariates, the hazard ratio is the change in infestation hazard for an increase of one-unit in a covariate (Zwiener, Blettner, & Hommel, 2011). The percentage change in infestation for every one-unit increase in a covariate is the exponentiated coefficient less '1', times 100 (Allison, 2010).

The variables l_i^p and l_i^n are regional dummy variables. The southwestern region of Oklahoma is the reference group. The expected sign of the coefficient on the northern and western region dummy variables is negative because SCA typically move south to north.

The d_i^1 covariate (distance between sorghum fields in Oklahoma and the last observed field in Texas infested by SCA) controls for northward movement of SCA from its origin as a function of distance. The variable d_i^2 is the distance between the first infested field in the southwest region of Oklahoma and all other Oklahoma sorghum fields. The variable d_i^3 is the distance between the sorghum field where SCA infestation was first reported in a region (as indicated by the dummy variables; southwest, north-central, north-east), and all other sorghum fields in the region. The variable d_i^4 is the distance between an infested field in period t and the most recently infested field in $t-1$. The distance variables were scaled by 100 for interpretability. The expected signs of the coefficients for all distance covariates are negative, meaning that the hazard of infestation is expected to decrease as the distance between fields increases.

The variables ta_i, ra_i, and an_i are temperature, precipitation, and the wind direction angle, respectively, for field i. These are the median values of the kriged surfaces for each field, with the median value taken over t = 0 up to the infestation date (details follow). For uninfected fields, the median values over the 139-day study period were used. The expected sign of temperature on the time until a field was infested is negative. Research finds that SCA only reproduce in the temperature range of 10 to 30°C, and that fertility and longevity decrease outside this temperature range (De Souza et al., 2019). The median field temperature over the study period was 24°C (minimum (maximum) of 19 (27) °C). This range is ideal for SCA reproduction. It is hypothesized that temperatures outside this range will negatively affect SCA survival (De Souza et al., 2019). Precipitation negatively affects the survivability of SCA. The expected sign of precipitation on field infestation is negative. The expected sign of the wind direction angle on SCA infestation is positive. An increase in the wind direction angle indicates a shift in wind direction from the northeast to northwest. This shift is expected to positively correlate with SCA migration northward.

SCA population characteristics include the temporally lagged aphid population per sorghum plant and the temporally lagged ratio winged-total individuals per sorghum plant. The expected sign for the temporally lagged total population per plant is positive. Fields with a larger number of SCA populations at t – 1 are hypothesized to increase the likelihood of proximate fields becoming infested. The expected sign of the variable for the winged/un-winged ratio variable is positive, suggesting that proximity to a field that is infested with relatively more winged SCA in t – 1 increases the likelihood of a field becoming infested. Winged SCA are mobile over longer, field-to-field distances compared to un-winged individuals.

The underlying assumption of the PHM is that the relative hazard of becoming infested is constant over time. This assumption is not always justifiable, given the biological properties of SCA and geographic variability in weather (Kuitunen et al., 2021). If the effect of a covariate on a hazard varies over time, then the proportional hazard assumption is violated and statistical inference may be compromised (Nakamura, 1992). In this case, one solution may be to add a time-dependent covariate to the model.

The day-to-day correlation of weather and population characteristics may be associated with changes in the infestation hazard. Only the North-west region covariates reject the non-proportional hazard assumption. Since the region where a field is located and the distance between the fields is time-invariant, violation of the proportional hazard assumption for the northwest dummy covariate is unlikely. Therefore, time-dependent covariates are not added to the PHM model.

3.3 Ties and Exact Proportional Hazards Models

Tied events mean that multiple fields were reported to be infected at, or around, the same time (Xin, 2011). The likelihood a coefficient estimate is biased downward increases as ties become more frequent (Allison, 2010). Of the 35 infested fields, the number of tied fields with reports of infestation occurring on the same day was 31 (88.6%) (Appendix Tables 1 and 2 report the dates, field ID, the total SCA population per plant, and tied events).

Two partial likelihood methods proposed by Efron (1977), exact and discrete, provide a better approximation of the hazard function when data are tied. The exact partial likelihood method assumes there is an unknown ordering with respect to infestation events, whereas the discrete method assumes that infestation events occurred at exactly the same time (Allison, 2010). During the study period (May 31 to October 16; 139 days), 47 sorghum fields were surveyed at an irregular frequency for each field. For infested fields, SCA could have migrated there before the date fields were surveyed. For example, an infestation report was made on August 30 for field 23. The fields on which infestation was reported for August 30 are 19, 23, 24, 27, 28, and 34. It is assumed there is an unknown ordering of these infestation events since SCA infestation may have occurred on the same date, or at an earlier date, for these six fields. The exact partial likelihood method attends to this issue and it is used here. In this study, the PROC PHREG procedure (SAS 9.4 software) is used for the proportional hazard model.

3.4 Data

Data were obtained from the United States Department of Agricultural Research Station in Stillwater, Oklahoma personal communication (Elliott, 2021). Data were collected in 2017 from 47 Oklahoma sorghum fields (Appendix Table 1, "Field statistics"). Observations were made on multiple days at an irregular frequency, ranging from one to 14-day intervals. Data collection resulted in 433 observations for the 47 sorghum fields surveyed. The number of observation days is 139 for all fields, spanning from May 31 to October 16, 2017.

A field was considered infested if winged or wingless SCA were identified on sorghum plants. The period from May 31 to the observed infestation date marks the time (t, days) until a field was infested. If the field was never infested from May 31 to October 16, then it received a '0'. The '0' indicator censors un-infested fields. In this study, the date until the first infestation of the field is used, not the date when the field is infested. The date until the first infestation occurs is used as the dependent variable in the survival model (Allison, 2010). For example, an infestation reported on August 16 corresponds with a period of 77 un-infested days. 34 of Oklahoma's 47 sorghum fields were infested during the data collection period, with the remaining 12 fields classified as un-infested on October 16 (Table 2).

The covariates included in the SCA migration model fall into three categories: geographic relationships between sampled sorghum fields, weather variables, and SCA population characteristics (Table 1).

Table 1. Covariate description

Category	Covariate	Description	Acronym	Source
Geographic relationship	Field location	North-central (*ncok*), north-west (*phok*), south-west (*swok*)	l^p, l^n	Norman Elliott (personal conversation, 2021)
	Distance	Distance (miles) between the first infested field and other fields in the region by region	d^1	Norman Elliott (personal conversation, 2021)
		Distance (miles) between the last infested sorghum field in Texas and the sorghum field in Oklahoma	d^2	Norman Elliott (personal conversation, 2021)
		Distance (miles) between the first sorghum field in Oklahoma and other fields in Oklahoma	d^3	Norman Elliott (personal conversation, 2021)
		Distance (miles) between sorghum fields infested in sequential time order	d^4	Norman Elliott (personal conversation, 2021)
Weather	Temperature	Temperature (°c) in sorghum field (average of all 5-minute averaged temperature observations each day)	ta	Oklahoma Mesonet (2020)
	Precipitation	Precipitation (mm) in sorghum field (liquid precipitation measured each day)	ra	Oklahoma Mesonet (2020)
	Wind direction	Wind direction angle (east: 0 degrees) in sorghum field (most common wind direction converted to degrees)	an	Oklahoma Mesonet (2020)
Sugarcane aphid population characteristics	Total population of SCA	Number of sugarcane aphids per plant	tp	Norman Elliott (personal conversation, 2021)
	Winged SCA ratio	Proportion of winged sugarcane aphid to total population of sugarcane aphid per plant	w	Norman Elliott (personal conversation, 2021)

3.5 Geographic Relationships between Sorghum Fields

Geographic proximity between sorghum fields is modeled using regional dummy variables and distances between sorghum fields. SCA infestations typically begin in the southern region of Oklahoma. SCA then migrate northward. Infestation occurred first in the southwest region (first sighting, May 31), followed by the north-central region, and finally the northwest region. Reporting dates for the north-central region occurred June 1 to October 3. Reporting dates for the northwest region were from July 7 to October 16 (Figure 1).

The division of Oklahoma's sorghum-producing areas into three regions controls for regional differences in landscape, soil quality, and other agroecological features. The 47 sorghum fields were situated in three distinct growing regions of Oklahoma: 11 sorghum fields were in the southwest region, 18 sorghum fields were in the north-central region, and 18 sorghum fields were in the northwest region of Oklahoma (Figure 1). Field-to-field distances were calculated using the Haversine formula. Distance variables are in miles.

Four distances were constructed. The first distance variable is the distance between the first field infested in a region to other fields in the same region. The second distance variable is the distance between the last infested sorghum field in Texas to all surveyed fields in Oklahoma. This variable controls for the northward movement of SCA from Texas to Oklahoma sorghum fields as a function of geographic distance.

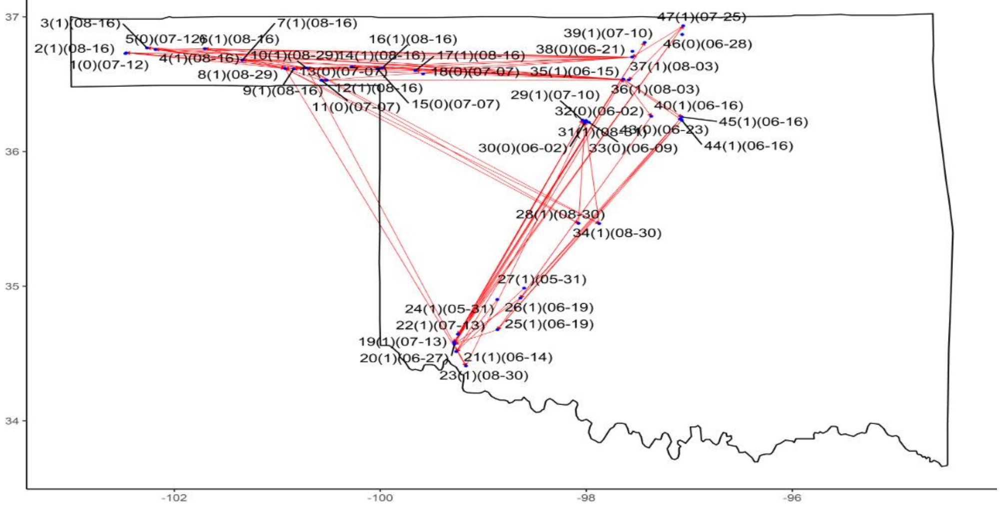

Figure 1. Oklahoma sorghum field location used for analysis, infestation status, and infestation date (or last reported date)

Note. Data from Oklahoma Mesonet (Mesonet, 2020). The number in each field indicates the field's identifier, if the field was infested ('1' if SCA present in the field, '0' otherwise), and the date of infestation. The red line indicates the chronological connection of the fields infested by SCA.

The third distance variable is the distance between the first sorghum field infested by SCA in Oklahoma to all other Oklahoma sorghum fields included in the survey. This variable also controls for the northward movement of SCA as a function of geographic distance. The fourth distance variable is the distance between infested fields in terms of temporal priority. Sequential field-to-field infestations distances were calculated for each surveyed field.

3.6 Weather Variables

Weather variables include temperature, precipitation, and wind direction. Studies on the biological effects of temperature and precipitation on SCA conclude that these two factors directly affect aphid mobility, reproduction, and survival (Boate & Otayor, 2020; Souza & Davis, 2020). Aphid movement is driven largely by atmospheric conditions (Irwin, Kampmeier, & Weisser, 2007). Winged SCA alatae are more likely to travel longer distances when atmospheric conditions are stable. Aphids cannot migrate over long distances during adverse, or unstable, weather conditions when temperature and precipitation are in flux (Isard & Gage, 2001; Isard et al., 1994).

Weather variables include average air temperature (TAVG), precipitation (RAIN), and the dominant wind direction (PDIR). All weather variables are from Oklahoma's Mesonet (Mesonet, 2020). There are 119 Mesonet stations in Oklahoma. Each station records daily observations on precipitation, wind speed, and temperature. TAVG is the average of all temperature observations at 5-minute interval each day (degrees Celsius). RAIN is precipitation measured each day (mm). PDIR is the most common wind direction recorded for a day, and is based on 16-point compass heading with a 16-point cardinal direction (Mesonet, 2020).

Weather variables were imputed for each sorghum field by generating kriged surfaces from data collected at each Mesonet station. Kriging is a geostatistical interpolation technique that generates predictions for unobserved locations using distance information between known data locations (Cressie, 2015; Paramasivam & Venkatramanan, 2019). Kriging was necessary because the weather variables were not measured at the study fields. Weather data were kriged for each of 139 days using a spherical semivariogram function: $\gamma(h) = C_0 + C \cdot \left(1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right) if\ h < a$, otherwise $\gamma = C_0 + C$, where γ is the semivariogram value, a is the effective range (distance), the distance at which the function reaches its maximum value, C is the variogram sill, C_0 is the variogram nugget (variance remaining after accounting for spatial covariance), h is the lag of separating distances between fields (Brooker, 1986; Burgess & Webster, 1980). Anisotropy was not detected for any weather variables. For each weather covariate, parameters were derived and used for each 139 days. For temperature, the mean of the range, sill, and nugget for 139 days was 2676.7, 9.1, and 0.1. The mean of the range, sill, and nugget for precipitation was 510.86, 0.2, and 0.04. The averages for the range, sill, and nugget over 139 days for wind direction are 1011.1, 4.7, and 2.3, respectively.

The (x,y)-coordinates of the kriged surfaces were matched with the (x,y)-coordinates of each of the 47 study fields for the period of 31 May to 16 October. The median values of a field's kriged weather variables over 139 days were used as field-level observations to minimize the effect of outliers and to arrive at a single, representative record for a field as required by the PHM data structure. For example, 210 of the 556 kriged precipitation values (139 days) were '0' for field ID 23, resulting in a highly skewed distribution (Skewness: 2.97). If there was an infestation reported on a study field, then the median of the field's weather variables for the period from the first day of observations to the infestation date was used as data. If the field was not infested 31 May to 16 October, the then median of the weather variable from the first observation date to the last observation date of the field was used. The resulting procedure generated a single vector of median kriged values for each weather variable and each of the 47 fields. Wind direction is a qualitative variable that ranges from 1 to 16. The 16-point directions were converted to an angle, with east set to 0 degrees.

Figure 2 shows the kriged medians for each weather variable. The average of the kriged median value for temperature is 24.96 °C. The average precipitation of Oklahoma for the kriged median value is 0.02 mm. The average of the kriged wind direction medians is 120.47 degrees (6.65 for 16-point cardinal direction; orients toward the northwest), A change from yellow to red in Figure 2 indicates an increase in a variable's value. In terms of temperature, the southern part of Oklahoma is relatively warm compared to other regions. For precipitation, eastern Oklahoma is comparatively wetter.

For the 16-point cardinal heading system of wind direction, '0' is north (= 90 degrees), '4' is east (= 0 degrees), '8' is south (= 270 degrees), and '12' is west (= 180 degrees). As the angle increases, the wind direction orients towards the west. The minimum and maximum wind direction values of 109.5 and 131.4 degrees indicate that the wind direction tended to orient toward the northwest during the study period.

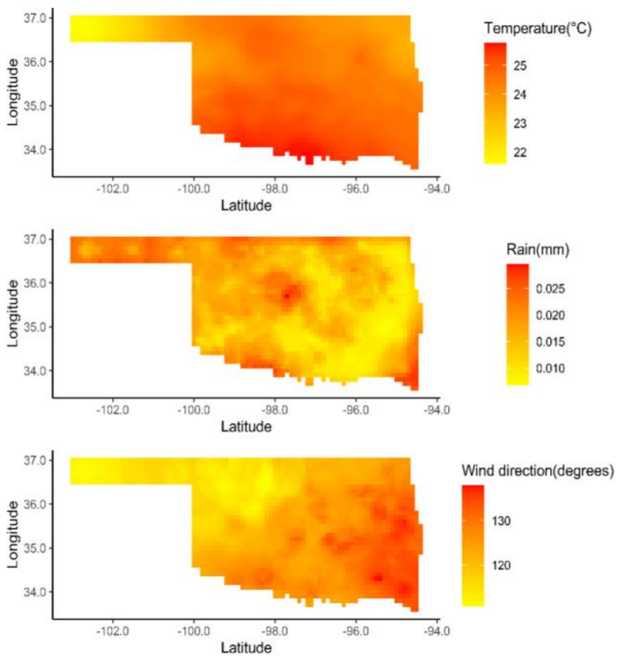

Figure 2. Median kriged values for temperature, precipitation, and wind direction

Note. Data from Oklahoma Mesonet (Mesonet, 2020).

3.7 Sugarcane Aphid Characteristics

Characteristics of SCA populations include the number of individuals per plant and the ratio of the number of winged SCA (alatae) to un-winged SCA (apterae) observed on a plant. The number of SCA individuals and the winged/un-winged ratio were matched to the next-infested field. That is, the winged/un-winged ratio is a temporally and spatially lagged variable. This is an important variable since winged individuals can use thermal updrafts to travel to distant fields.

Table 2. Covariate descriptive statistics

	Mean	Standard deviation	Min	Max	Range
Infestation	0.72	0.45	0	1	1
Period (days)	49.38	28.01	0	92	92
Distance to last field infested in Texas (miles)	207.61	72.14	105.46	317.89	212.43
Distance to first field infested in Oklahoma (miles)	116.87	66.27	0	260.77	260.77
Distance between the first infested field in a region and other fields in that region (miles)	39.67	30.41	0	106.47	106.47
Distance between temporally consecutive infested fields (miles)	43.76	66.25	0	290.44	290.44
Population per plant	11.66	75.60	0	518.78	518.78
Winged SCA ratio	0.05	0.09	0	0.33	0.33
TAVG (°c)	24.96	1.06	22.90	27.00	4.10
RAIN (mm)	0.02	0.01	0	0.04	0.04
PDIR (degrees)	120.47	6.02	109.50	131.40	21.90

Note. Data from Dr. Norman Elliott, USDA-ARS (personal communication, 2021), Oklahoma Mesonet (Mesonet, 2020).
[a] Infestation is indicated as '1' if the field is infested (the number of sugarcane aphid populations per plant is '0' or more) during the infestation investigation period, otherwise '0'. TAVG, RAIN, wind direction are the median of temperature, rainfall, and angle of wind direction variables from the first infestation date in Oklahoma to the first infestation date.

4. RESULTS

4.1 Infestation Likelihood Curves

Infestation likelihood curves demonstrate the univariate relationships between a covariate and the likelihood SCA infest a field (Figure 3). There is no statistical difference in the hazard of infestation between the "High" and "Low" variable groupings, except for the lagged ratio of the winged/un-winged ratio.

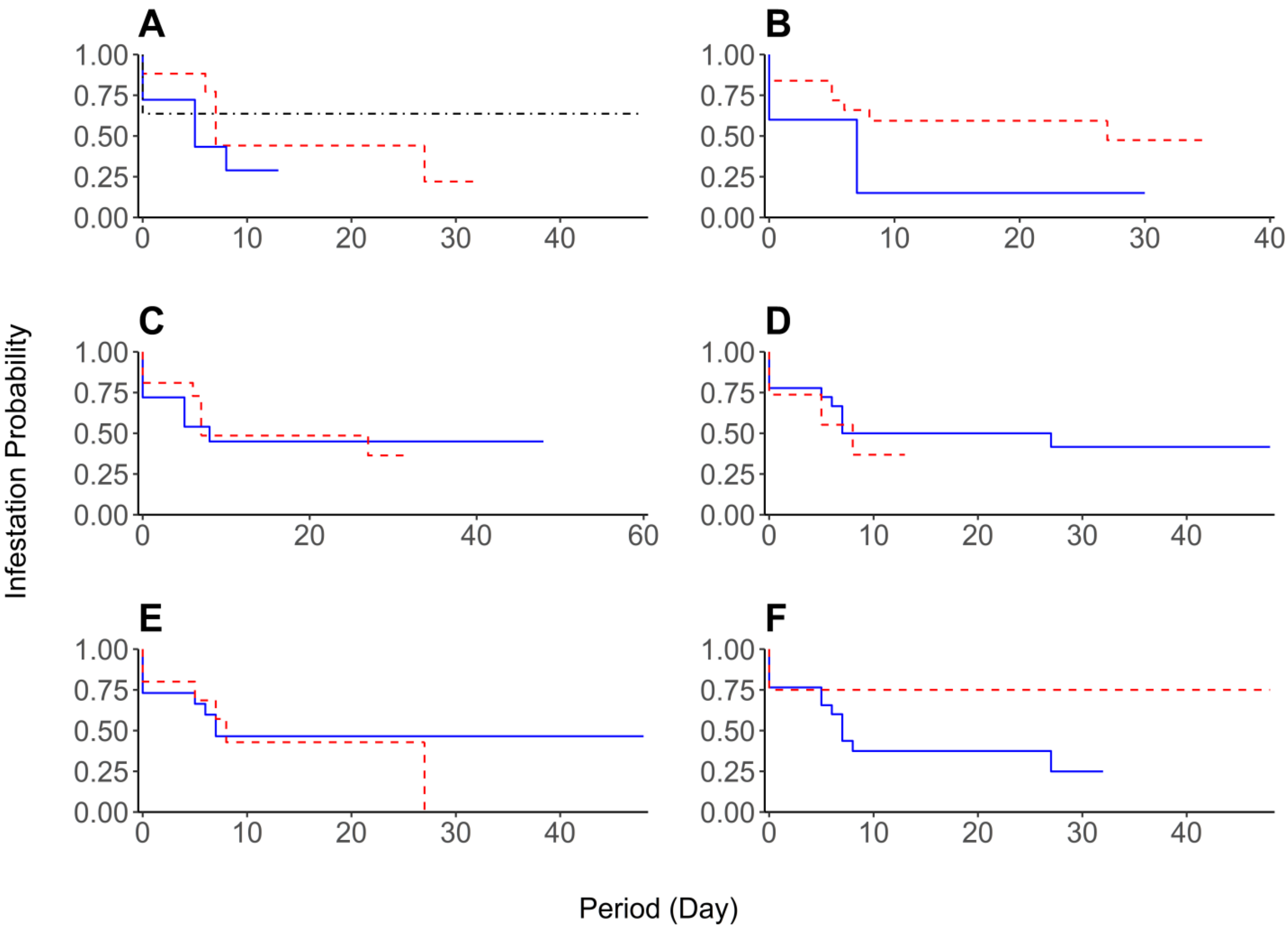

Figure 1. Sugarcane aphid infestation curves between groups of regions dummy variable (A), lagged wing ratio (B), distance between the last infested sorghum field in Texas and the sorghum field in Oklahoma (C), distance between the first sorghum field infested in Oklahoma to other sorghum fields in Oklahoma (D), distance between the first infested field and other fields in the region (E), distance between temporally consecutive infested fields (F) covariates.

Fields in southwestern Oklahoma appear to have a greater chance of infestation after eight days compared to the other regions (Figure 3-A). However, the log-rank and Wilcoxon statistics are 1.58 and 1.33, respectively, which means that the null hypothesis that the infestation probability between the three regions is the same cannot be rejected (Wilcoxon, 1992). In addition, there was no statistical difference in infestation curves between the southwestern and northwestern, and the southwestern and north-central regions. These results differ from the expectation that fields in the southwestern region of Oklahoma are relatively more susceptible to infestation. This finding is consistent with previous research that reports SCA can migrate over great distances during variable weather conditions (Suarez, Holway, & Case, 2001).

For the lagged winged/un-winged ratio covariate, the log-rank and Wilcoxon statistics are 4.3 and 3.96, respectively. The null hypothesis that there is no difference in the infestation probability for the 'High' and 'Low' groups is rejected. As shown in Figure 3-B, the infestation probability of the 'High' group is higher than that of the 'Low' group. Populations with lower wing/un-winged ratios are less mobile. This result is consistent with the expectation that infested fields with relatively higher proportions of winged to un-winged individuals increase the probability of other fields in proximity of becoming infested.

For the distance between the last infested sorghum field in Texas and the sorghum field in Oklahoma covariate (d^1), there is no difference in the probability of infestation between the 'High' and 'Low' groups (Figure 3-C). There is no difference in the infestation probability between the 'High' and 'Low' groups for the distance between the first sorghum field infested in Oklahoma to other sorghum fields in Oklahoma (d^2), the distance between the first infested field and other fields in the region (d^3), and the distance between temporally consecutive infested fields covariate (d^4) (Figure 3-D, 3-E, 3-F).

The infestation probability curves calculated with each of the four distance covariates suggest that the difference in distance between fields in Oklahoma does not influence the time until a field is infested. This finding suggests that it may be difficult for sorghum producers to establish insect control plans based on field proximity. Knowing when SCA appeared in north Texas may be the most important source of information since SCA generally migrate northward. However, information on the wing/un-winged populations in the previously infested field may be useful information for establishing insect control plans and predicting where SCA will migrate.

4.2 Proportional Hazard Regression

The likelihood ratio and the Wald chi-square statistics are large enough to reject the null hypothesis that the variables included in the regression have a joint zero effect on the infestation hazard at the 1% significance level (Table 3). All covariates in the geographic relationship category were uncorrelated with the SCA infestation hazard. The regional dummy covariates and the distance between the sorghum fields were unassociated with the infestation hazard. Studies on the long-distance migration and dispersion activity of SCA may explain why field proximity and distance to other fields were uncorrelated with the likelihood of infestation.

Table 3. Cox proportional hazards model results

Category	Covariate	Estimate	Standard Error	Hazard ratio	Infestation probability
Geographic relationship	North-west region	-1.126	2.256	0.324	0.245
	North-central region	0.536	4.149	1.710	0.631
	Distance between the last infested sorghum field in Texas and the sorghum field in Oklahoma	-0.942	3.552	0.390	0.281
	Distance between the first sorghum field in Oklahoma and other fields in Oklahoma	0.510	2.263	1.665	0.625
	Distance between the first infested field and other fields in the region	-1.936	1.939	0.144	0.126
	Distance between temporally consecutive infested fields	0.398	0.309	1.489	0.598
Weather	Temperature	-0.696*	0.419	0.499	0.333
	Precipitation	-10.570**	4.503	0.000	0.000
	Wind direction	-0.129*	0.070	0.879	0.468
Sugarcane aphid population characteristics	Total SCA population	-0.039*	0.013	0.962	0.490
	Winged SCA ratio	-4.186	5.077	0.015	0.015
Likelihood ratio	75.62***				
Wald χ^2	117.83***				
Likelihood	66.57				
AIC	88.58				
SBC	105.69				

Note. *** Significant difference at the .01 level; ** Significant difference at the .05 level; * Significant difference at the .10 level

Temperature, precipitation, and wind direction affect the hazard of infestation at the 10% level of significance, respectively (Table 3). An increase in temperature is associated with a decrease in the likelihood of SCA infestation. For a 1°C increase in temperature, the infestation hazard decreases by 50.1% (=100 × [exp (-0.696) – 1]). This result is consistent with the expected sign of this variable. The temperature range over the study period was 18 to 27 °C, and the median temperature was 24 °C, all of which are favorable temperatures for SCA reproduction. Studies on SCA fertility and longevity indicate that populations decrease outside the temperature range of 10 to 30 °C (De Souza et al., 2019). The probability of infestation for the temperature covariate was 0.33 (= odds ratio of ta/ (1 + odds ratio of ta). An increase in precipitation reduces the probability of SCA infestation.

A 1-mm increase in precipitation reduces the hazard of infestation by 99.99%. This finding suggests precipitation reduces the hazard of infestation due caused by rain.

The more frequently wind direction changed from northeast to northwest (0 degrees, then to the east at 90 degrees), the lower was the infestation hazard. A 1-degree change in wind direction decreased the infestation hazard by 12.1%. The infestation probability for the wind direction covariate was 0.468.

Total SCA populations were uncorrelated with the hazard of infestation, but the proportion of winged SCA in the most recent field was negatively associated with the likelihood of infestation. These findings differ from the *a priori* expectations, but are consistent with the notion that SCA transmission occurs over longer distances, given favorable weather conditions.

5. CONCLUSIONS

The purpose of this study was to measure the effects of weather, geographic, and biological characteristics of SCA on the infestation of sorghum fields in Oklahoma. This is the first study to evaluate the effects of field proximity, weather, and SCA biology on infestation at the field level for Southern Great Plains sorghum producers. Temperature, precipitation, and wind direction were hypothesized to be closely related to the survival and migration of SCA. Geographical characteristics used in this study include between-field distance and locational information. Geographical characteristics were uncorrelated with SCA survival and migration. Total SCA population per plant was correlated with the migration of SCA and field infestation.

Infestation likelihood curves suggest there is a difference in the infestation probability between the high- and low-density wing/un-winged SCA groups. The larger the ratio of winged to un-winged SCA, the more likely their movement to other sorghum fields.

Temperature, precipitation, and wind direction were negatively correlated with SCA infestation hazards. A decrease in the likelihood of infestation due to an increase in precipitation was associated with a decrease in the likelihood of a field becoming infested. Infestation hazards are lower when prevailing winds change from northeast to northwest. As mentioned in previous studies on pest infestation prediction modeling, weather is an important determinant of infestation hazard. However, field location and the distance between fields was not a significant factor in the present study.

Studies on pests and disease management strategies suggest the need for prediction models based on weather and climate (Bhagwan et al., 2022; Marini, Rizzoli, & Tagliapietra, 2022). The results of this study reaffirm the value of including weather data on temperature, precipitation, and wind direction to predict the movement of SCA. Brown et al. (2022) notes that the use of geospatial data in early warning systems for pest and disease risk can be used to estimate potential risks. Findings from this study suggest that geospatial data (field regions and distances between fields) may not be as important as previously suspected for the infestation of sorghum fields.

Despite the limited number of field observations available for the analysis, a contribution of this study is the field-level analysis of SCA infestation of sorghum fields. As mentioned by previous studies, depending on data availability, it may be possible to measure the influence of other factors that affect SCA infestation, such as infestation dynamics and food density. In addition, the infestation curve and PHM results provide field-level information about more detailed infestation hazard. These aids may improve field-level decision making for pest control planning, such as coordination of pesticide use and harvest timing.

Recommended policy actions include developing a pest early detection system to track SCA infestations in real time. Current efforts have been limited primarily to county-level reporting through local extension offices. Statewide efforts have been initiated to provide composite mappings of pest reporting, but efforts to regionalize reporting have been less successful. A critical constraint has been limited participation in early warning detection efforts among producers due to the voluntary nature of participation. Many producers may by unfamiliar with pest reporting programs. State extension agencies should increase the visibility and awareness of their pest scouting programs and consider requiring producers to provide a pest scouting and reporting action plan to participate their extension programing network. Active participation by producers is required to generate the data needed to operationalize an early warning system, because it remains unlikely that satellite imagery or related remote sensing technologies will be able to substitute for manually based scouting approaches. The data currently available on SCA infestation is limited and makes it difficult to validate tracking models as illustrated in this paper.

The hazard equations explaining SCA movement could be expanded with future research to include the life-cycle growth and development of SCA colonies across their range of metamorphosis, including the transition from nymphs, instars, and adults and processes such as molting. This information would be particularly required for modeling SCA movement across an entire season. The current model includes the proportion of alleles as an exogenous variable, but the polymorphic lifecycle of SCA is determined through interactions with the host plant and by weather. The hazard model is based on migration, so additional variables could be included to model the lifecycle, and alternative forms of sexual and asexual reproduction from nymph to adults, to explain the proportion of winged (alleles) to non-winged (apterous) variants when that data become available. The latter could be of particular importance because water-stressed plants are typically more susceptible to phytophagous insects due to increased nitrogen availability. Future modeling could include a broader geographic scope and a longer time span encompassing earlier migratory movements. SCA are believed to begin migrating northward in early spring from southern Texas, near latitudes where temperatures never fall below freezing. An expanded set of observations could include a wider range of weather patterns and provide regional rather than state-level forecasts of SCA movement. Weather variability and extreme events could also be included to model non-linearity associated with for example extreme, fluctuating temperatures. Finally, machine-learning methods for analyzing SCA migration could be explored as "big data" collected from a pest early warning system become more widely available.

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Appendices

Appendix Table 1. Field statistics

Id	Region	Infestation	Last Report (m/d)	Period (day)	Wing	Distance to Field in Region (mile)	Distance to Last Field Infested in Texas (mile)	Distance to First South Field Infested in Oklahoma (mile)	Distance between Temporally Consecutive Infested fields (mile)	Population per Plant	TAVG (°C)	RAIN (mm)	Wind Direction Angle (degree)
1	ph	0	7/12	42	0	106	105	261	0	0	24.1	0.026	109.5
2	ph	1	8/16	77	1	106	106	260	11	0.25	23.5	0.028	122.2
3	ph	1	8/16	77	0	95	108	251	5	0.02	23.6	0.034	122.9
4	ph	1	8/16	77	1	91	108	246	27	0.03	23.7	0.035	122.9
5	ph	0	7/12	42	0	91	108	246	27	0	24.2	0.030	113.7
6	ph	1	8/16	77	1	65	113	222	21	0.25	24.2	0.034	122.4
7	ph	1	8/16	77	1	44	116	201	28	3.28	24.3	0.031	124.4
8	ph	1	8/29	90	1	21	125	178	12	0.84	24.2	0.035	126.8
9	ph	1	8/16	77	0	16	128	174	16	0.06	25.2	0.037	127.9
10	ph	1	8/29	90	1	10	133	168	176	1.61	24.5	0.034	126.1
11	ph	0	7/12	42	0	0	134	158	0	0	25.4	0.030	123.5
12	ph	1	8/16	77	0	0	135	158	18	0.02	25.5	0.034	126.9
13	ph	0	7/7/	37	0	3	136	155	0	0	24.1	0.028	123.6
14	ph	1	8/16	77	1	18	151	147	16	0.19	25.8	0.026	127.8
15	ph	0	7/7/	37	0	31	162	135	0	0	24.3	0.028	121.6
16	ph	1	8/16	77	1	33	164	133	18	0.29	25.9	0.031	128.4
17	ph	1	8/16	77	0	51	178	118	70	0.05	25.9	0.031	123.5
18	ph	0	7/12	42	0	55	181	114	0	0	25.5	0.031	118.8
19	sw	1	7/13	43	1	32	178	92	5	2.08	27.0	0.014	123.5
20	sw	1	6/27	27	0	33	179	92	135	0.01	26.0	0.006	131.4
21	sw	1	6/14	14	1	35	181	94	167	0.03	24.1	0.009	125.1
22	sw	1	7/13	43	1	28	179	87	203	6.99	26.8	0.018	124.5
23	sw	1	8/30	91	1	38	188	96	96	0.03	26.7	0.028	128.7
24	sw	1	5/31	0	1	0	197	59	16	0.08	23.3	0.000	109.5
25	sw	1	6/19	19	0	15	200	70	21	0.04	24.5	0.006	121.9
26	sw	1	6/19	19	1	13	210	50	43	0.03	24.1	0.008	118.0
27	sw	1	5/31	0	1	16	211	45	50	0.06	22.9	0.001	109.5
28	sw	1	8/30	91	1	59	241	0	11	9.1	25.9	0.029	127.0
29	nc	1	7/10	40	0	2	251	53	52	0.06	25.5	0.033	120.6
30	nc	0	6/21	21	0	0	252	52	0	0	24.6	0.032	112.5
31	nc	1	8/31	92	0	0	252	52	0	0.59	26.0	0.030	121.6
32	nc	0	6/21	21	0	1	253	53	0	0	24.6	0.032	112.5
33	nc	0	6/21	21	0	2	254	52	0	0	24.6	0.032	112.5
34	sw	1	8/30	91	1	68	252	11	53	518.78	25.8	0.031	129.6
35	nc	1	6/15	15	0	31	278	78	24	0.08	24.2	0.013	111.2
36	nc	1	8/3/	64	1	32	281	79	12	0.02	26.9	0.014	118.4
37	nc	1	8/3/	64	1	42	287	90	30	0.18	26.8	0.016	115.6
38	nc	0	7/10	40	0	45	288	93	0	0	25.0	0.018	116.7
39	nc	1	7/10	40	0	52	295	100	186	0.06	24.9	0.017	116.4
40	nc	1	6/16	16	0	36	288	68	17	0.02	24.1	0.008	109.5
41	nc	1	8/3/	64	0	73	312	120	290	2.69	26.1	0.023	122.3
42	nc	1	7/25	55	0	74	315	121	11	0.01	26.1	0.019	120.2
43	nc	0	6/23	23	0	52	303	77	0	0	24.6	0.006	121.3
44	nc	1	6/16	16	1	53	304	77	2	0.01	24.0	0.005	114.6
45	nc	1	6/16	16	0	53	304	78	149	0.02	24.0	0.005	113.9
46	nc	0	6/28	28	0	69	316	112	0	0	24.3	0.013	119.5
47	nc	0	7/25	55	1	73	318	116	40	0.05	26.0	0.016	121.1

Note. Data from Data from Dr. Norman Elliott, USDA-ARS (personal communication, 2021), Oklahoma Mesonet (Mesonet, 2020).

[a] Region means the northwest (ph), southwest (sw), and north-central (nc) regions, respectively. Infestation means that the sugarcane aphid population per plant is positive and the field is infested during the infestation investigation period. The last report means the date of the first infestation if there is an infestation, and the date of the last investigation if there is no infestation. Period means the difference between the first infestation (May 31) and the date of infestation or the last investigation in each field. wing means that the field is infested with alatae with wings. Distance to field in region is the distance between the first infested field for each local region and other fields in the region. Distance to last field infested in Texas is the distance between the last infested sorghum field in Texas and the sorghum field in Oklahoma. Distance to first south field infested in Oklahoma is distance between the sorghum field where the first infestation occurred in Oklahoma and other fields in Oklahoma. The population per plant is the number of wing/wingless sugarcane aphid per sorghum plant. TAVG, RAIN, Angle are the median of temperature, rainfall, and angle of wind direction variables from the first infestation date in Oklahoma to the first infestation date.

Appendix Table 2. Field ties by date of infestation report

Date (M/D)	Number of Tie Fields	ID	Total Population per Plant	Region	Latitude	Longitude
05/31	2	24	0.08	swok	34.900	-98.864
		27	0.06	swok	34.985	-98.603
06/16	3	40	0.02	ncok	36.262	-97.369
		44	0.01	ncok	36.232	-97.073
		45	0.02	ncok	36.257	-97.073
06/19	2	25	0.04	swok	34.677	-98.862
		26	0.03	swok	34.912	-98.639
07/10	2	29	0.06	ncok	36.233	-98.036
		39	0.06	ncok	36.810	-97.433
07/13	2	19	2.08	swok	34.585	-99.283
		22	6.99	swok	34.644	-99.246
07/25	2	42	0.01	ncok	37.059	-97.181
		47	0.05	ncok	36.934	-97.058
08/03	3	36	0.02	ncok	36.532	-97.586
		37	0.18	ncok	36.702	-97.554
		41	2.69	ncok	37.056	-97.231
08/16	10	2	0.25	phok	36.733	-102.466
		3	0.02	phok	36.769	-102.264
		4	0.03	phok	36.758	-102.182
		6	0.25	phok	36.765	-101.703
		7	3.28	phok	36.679	-101.339
		9	0.06	phok	36.615	-100.841
		12	0.02	phok	36.529	-100.568
		14	0.19	phok	36.630	-100.277
		16	0.29	phok	36.621	-99.982
		17	0.05	phok	36.601	-99.660
08/29	2	8	0.84	phok	36.617	-100.925
		10	1.61	phok	36.620	-100.714
08/30	3	23	0.03	swok	34.407	-99.168
		28	9.1	swok	35.467	-98.076
		34	518.78	swok	35.465	-97.874

Note. Data from Dr. Norman Elliott, USDA-ARS (personal communication, 2021).
[a] Region means the northwest (ph), southwest (sw), and north-central (nc) regions, respectively.