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Degree-Day Prediction Models for the Flight Phenology of Western Bean Cutworm (Lepidoptera: Noctuidae) Assessed with the Concordance Correlation Coefficient

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Abstract

Western bean cutworm, *Striacosta albicosta* (Smith) (Lepidoptera: Noctuidae), is a native, univoltine pest of corn and dry beans in North America. The current degree-day model for predicting a specified percentage of yearly moth flight involves heat unit accumulation above 10°C after 1 May. However, because the moth's observed range has expanded into the northern and eastern United States, there is concern that suitable temperatures before May could allow for significant *S. albicosta* development. Daily blacklight moth catch and temperature data from four Nebraska locations were used to construct degree-day models using simple or sine-wave methods, starting dates between 1 January and 1 May, and lower (−5 to 15°C) and upper (20 to 43.3°C) developmental thresholds. Predicted dates of flight from these models were compared with observed flight dates using independent datasets to assess model performance. Model performance was assessed with the concordance correlation coefficient to concurrently evaluate precision and accuracy. The best model for predicting timing of *S. albicosta* flight used simple degree-day calculations beginning on 1 March, a 3.3°C (38°F) lower threshold, and a 23.9°C (75°F) upper threshold. The revised cumulative flight model indicated field scouting to estimate moth egg density at the time of 25% flight should begin when 1,432 degree-days (2,577 degree-days °F) have accumulated. These results underscore the importance of assessing multiple parameters in phenological models and utilizing appropriate assessment methods, which in this case may allow for improved timing of field scouting for *S. albicosta*.

Keywords: *Striacosta albicosta*, degree-days, concordance correlation coefficient, delta-method

Western bean cutworm, *Striacosta albicosta* (Smith) (Lepidoptera: Noctuidae), is a native, univoltine pest of corn and dry beans in North America (Horner 1948, Antonelli 1974). In recent years, significant western bean cutworm infestations have been observed in corn beyond the previously described range in the west-central United States (Miller et al. 2009). *S. albicosta* has been documented north to Iowa and southern Minnesota, east to Massachusetts, and south into Mexico (O'Rourke and Hutchison 2000, Rice 2000, Michel et al. 2010, PSU *Pestwatch* 2014 website). Female moths oviposit during mid-summer, and larvae feed within the corn ear causing damage to kernels (Holtzer 1983). This range expansion has increased the need for scouting methods and insecticide treatments to prevent yield loss where *S. albicosta* previously was not present or did not cause significant yield loss (Michel et al. 2010).

S. albicosta overwinter as prepupae in the soil and emerge as adults the following late-spring and summer (Michel et al. 2010, Hanson et al. 2013). Females oviposit during July in most regions, and are most attracted to tassels

ing corn (Holtzer 1983). Early instars feed initially on leaf surfaces, but soon migrate to developing ears and cause substantial kernel damage (Holtzer 1983, Eichenseer et al. 2008, Paula-Moraes et al. 2013). Because larvae inside ears are not exposed to insecticides, applications should occur between times of oviposition and entry into ears (Hagen 1962, Paula-Moraes et al. 2013). Field scouting for egg masses is recommended between 25–50% cumulative annual moth flight when oviposition rates are highest (Paula-Moraes et al. 2011). Control treatments would be recommended if >4–8% of field corn plants were infested with egg masses or larvae (Appel et al. 1993, Paula-Moraes et al. 2011).

Growers and crop consultants often use degree-day models to predict timing of insect pest activity in the field (e.g., Philips et al. 2012, Nam et al. 2013). Timing of *S. albicosta* flight has traditionally been predicted using simple degree-days, calculated from averages of daily minimum and maximum air temperatures and a base of 10°C beginning 1 May (e.g., Seymour et al. 2010). Flight percentages of 25, 50, and 75% are predicted to occur when accumulated degree-days reach 733, 790, and 853, respectively. This model was de-

Table 1. Descriptive statistics for study sites ordered south to north and numbers and timing of *S. albicosta* moths captured in black light traps at Nebraska sample sites, 1981–2009

Study site	Trap coordinates		Weather station ID	No. years*	Median moths per year	Mean 25% flight date ($\pm$ SD)	Range
Clay Center	40.58 N	92.14 W	257899	15	1,087	11 July (7.2)	30 June–25 July
Aurora	40.83 N	98.05 W	250445	14	577	12 July (6.5)	3–28 July
North Platte	41.10 N	100.77 W	256079	22	1,318	16 July (6.3)	9–30 July
Concord	42.38 N	96.96 W	256019**	22	1,046	18 July (6.8)	5–28 July

Median moths captured per year at each site are shown because the data were not normally distributed, while the data for the date of 25% flight were normally distributed.

* Results were excluded because annual totals were <25 moths from Concord (1982–1983 and 1985–1989), North Platte (2000 and 2004), and Clay Center (1998).

** Weather data from Wayne, NE (ID: 259 045) replaced missing data in 1998–2007 and 2009, and Haskell lab (ID: 253 652) in 2008.

veloped by Ahmad (1979), using data from daily black light traps that characterized timing of moth flights in 24 independent site-years (i.e., a year at a single location) scattered in 1958–1974 at seven locations in Nebraska. The Ahmad model has since been used extensively by extension entomologists and crop consultants throughout the Midwest region (e.g., Seymour et al. 2010).

Reexamination of the Ahmad model was prompted by reports from the northeastern Great Lakes region that suggested the current model might not accurately predict moth timing of flight in the area (Michel et al. 2010). Of particular concern was the start date of 1 May, before which diapause could cease and temperature-driven insect development could occur. Additionally, the Ahmad model had not been validated at independent locations (Picard & Cook 1984). To determine if predictions of *S. albicosta* flight could be improved, we examined alternative degree-day models involving different calculation methods, starting dates, lower thresholds, and upper threshold temperatures to predict when 25% cumulative flight would occur. We then used the chosen degree-day parameters to develop a predictive model of cumulative percent flight throughout the year. The Ahmad (1979) model and newly proposed models were compared to choose the best model for forecasting moth flights.

Materials and Methods

Monitoring Moth Flights. Black light traps were used to monitor *S. albicosta* moth flights and characterize phenology patterns at field sites near corn fields in four Nebraska locations over multiple years: Aurora (1981–1988 and 2000–2005) and Clay Center (1994–2009) in southeastern NE, Concord (1981–2009) in northeastern NE, and North Platte (1986–2009) in central NE. Black light traps were used because they capture both males and females (Mahrt et al. 1987). Traps consisted of a black light placed ~1.5m above ground level, with a metal funnel and canister below and use of a moth killing agent (Mahrt et al. 1987). Traps were operated from May 1 to August 31 to include observations before and after the flight season at each site-year. The number of captured males and females combined was recorded daily. In cases where the traps were not checked daily (e.g., weekends), the total

moth catch over that period was prorated over those days (Ahmad 1979).

Cumulative percent emergence by day of year was calculated for each site-year, by dividing the accumulated number of moths captured by the total number caught that year, and multiplying by 100. Dates when cumulative catches first exceeded 25% ($D_{25\%}$) were noted. Data from individual site-years were excluded if annual catch was <25 moths.

Weather Data. Series of daily low and high temperatures were obtained from the National Oceanic and Atmospheric Administration weather stations that best matched the flight monitoring sites and years (High Plains Regional Climate Center [HPRCC] 2010). Due to missing observations at the Concord weather station after 1997, weather data from nearby Wayne (~19 km) replaced missing data except in 2008 when data were available from the nearby University of Nebraska Haskell lab station in Concord (Table 1).

Model Development. Data from half of the years at each site were randomly chosen to be used for model development ($n = 37$ site-years) and the remaining data were designated for model validation ($n = 36$; Table 2). Alternative flight phenology models consisted of a factorial arrangement of two degree-day calculation methods, five starting days of year for degree-day accumulation, 37 lower development thresholds, and 43 upper development thresholds, for a grand total of 15,910 parameter combinations.

Two methods were used to calculate daily degreedays from each of the development site-year weather datasets. The first method was the simple method, where degree-days for a given day were estimated as the mean of the day's extreme temperatures (high and low) minus a lower threshold. If the daily mean was below the lower threshold, the lower threshold was used in place of the daily mean (McMaster and Wilhelm 1997). If the daily mean was above the upper threshold, then the upper threshold was used in place of the daily mean. For example, if a model with a lower threshold of 10°C was used on a day with a high of 20°C and a low of 5°C, 2.5 degree-days would accumulate that day.

The second method was the half-day sine-wave method (Allen 1976), where degree-days were estimated with sine wave integration between the low and high temperature during the day, and the high temperature of the current

Table 2. Model development and validation datasets by location

Location	Development dataset years	Validation dataset years
Aurora	1981–1982, 1984–1985, 1987–1988, 2004	1983, 1986, 2000–2003, 2005
Clay Center	1994–1997, 2001, 2003–2004, 2008	1999, 2002, 2005–2007, 2009
Concord	1984, 1990, 1993, 1995–1997, 2000–2002, 2005, 2007	1981, 1991–1992, 1994, 1998–1999, 2003–2004, 2006, 2008–2009
North Platte	1989–1990, 1993–1995, 1998, 2001–2003, 2006, 2009	1986–1988, 1991–1992, 1996–1997, 1999, 2005, 2007–2008

Clay Center 1998, Concord 1982–1983, 1985–1989, and North Platte 2000 and 2004 excluded due to <25 annual adult catch or missing data.

day and the low of the next day. With both methods, degree-days accumulations up to a given date were to the time of the minimum temperature in the day's morning.

Candidate starting days for degree-day accumulations were days 1, 32, 50, 91, and 121 of each year (i.e., approximately the beginning of each month from January to May, depending on leap year). Candidate lower development thresholds ranged in 0.56°C (1°F) increments from –5 to 15°C (23 to 59°F), and upper thresholds also ranged in 0.56°C increments from 20 to 43.33°C (68 to 110°F). The highest temperature recorded across all locations during study years was 42.78°C (109°F), so a 43.33°C upper threshold was equivalent to having no upper threshold in a model. Degree-day calculations and summations for all 15,910 models were performed in SAS 9.3 (SAS Institute, 2014) using a simple grid search process iterating through each combination of calculation method, start date, lower threshold, and upper threshold parameters.

For each model, predicted D_{25%} was derived for each of the 37 site-years in the development dataset by first determining the degree-days that had accumulated at the observed D_{25%}, and then averaging those degree-day totals to obtain a mean for the 37 yr. In turn, the predicted day in each site-year was obtained by determining the day when the average degree-day total had accumulated.

Performance of the alternative models was assessed by examining agreement between observed and predicted D_{25%} flight days using regressions of observed (*y*) on predicted (*x*) days from the 37 cases (Piñeiro et al. 2008). An ideal model would be both precise and accurate, as evidenced by a correlation coefficient $r = 1$, and a least squares regression line of $y = x$ (see Tedeschi 2006). These two aspects are reflected in the single number concordance correlation coefficient (*CCC*),

$$CCC = rA \quad [1]$$

which is the product of r and accuracy A (Lin 1989, Lin et al. 2002, Liao 2003). Accuracy was calculated as

$$A = \frac{4 s_o s_p - r [s_o^2 + s_p^2]}{[2 - r] [s_o^2 + s_p^2] + \Delta^2} \quad [2]$$

where s_p and s_o were standard deviations in a sample of matching predicted and observed days, respectively, and Δ was the difference between means of observed and predicted days. Concordance correlation coefficients can range

theoretically from –1 to 1, but in most situations are between 0 (where predictions are neither precise nor accurate) and 1 (where predictions are perfectly precise and accurate) (Meek et al. 2009). The model with the highest *CCC* for each degree-day calculation method was selected for further validation.

Confidence limits for lower and upper developmental thresholds selected for each calculation method were obtained through polynomial regression and the delta method (Powell 2007). Values of calculated *CCCs* at each lower and upper threshold combination were regressed as second order polynomial functions of lower and upper development thresholds (e.g., lower threshold + lower threshold squared). The delta method was used to calculate 95% confidence limits for the selected threshold values. Regression and delta method calculations were done with *Arc* software (Cook and Weisberg 2004).

Model Validation. To independently evaluate Ahmad's (1979) original model, and to compare it with the best revised model for each degree-day calculation method, we calculated predicted D_{25%} with each of the three models from the temperature series from the 36 independent validation site-years. We then calculated *CCCs* to assess agreement between predicted and observed flight days to select a model for future use. Means and standard deviations of errors in predictions (predicted – observed days) were also calculated to evaluate each model's bias and precision.

Seasonal Flight Distributions. To determine how well the selected calculation method, start date, and lower and upper thresholds derived from D_{25%} could predict entire annual flight distributions, values for cumulative moth capture were converted to percentages of annual totals at each development site-year, and then regressed against accumulated degree-days, as calculated with the chosen model (e.g., Régnière 1984, Broatch et al. 2006, Nam and Choi 2014). The pattern in cumulative flight was then analyzed using three alternative probability distribution functions. We first tried a logistic function,

$$\% \text{ annual flight} = \frac{100}{1 + e^{-\left(\frac{D-\mu}{s}\right)}} \quad [3]$$

where D was accumulated degree-days, and μ and s were parameters for location and scale, respectively. Second was a log-logistic function, substituting $\ln(D)$ for D into equation [3]. The third function was a Weibull distribution,

Figure 1. Cumulative percentages of annual totals of moths captured in years when totals exceeded 25 moths per year in the development dataset at Aurora (1981–1988 and 2000–2005), Clay Center (1994–2009), Concord (1981–2009), and North Platte (1986–2009), NE. Lines represent observed percentages for individual years.

$$\% \text{ annual flight} = \frac{100}{1 - e^{-\left(\frac{D}{s}\right)^k}} \quad [4]$$

where k was the shape parameter. Parameters for the three functions were estimated with PROC LIFEREG in SAS, which is commonly used for survival and failure time analyses (Tein and MacKinnon 2003). Model adequacy for each function was assessed using the Akaike information criterion (AIC) to determine the best fitting distribution where a distribution with a lower AIC had a relatively better fit amongst the three distributions (Burnham and Anderson 1998).

Estimates of μ and s for the log-logistic function were then used to calculate degree-days corresponding with arbitrary levels of flight through the season using the development dataset. The delta method was used to calculate 95% confidence intervals for those degree-day timepoints (Powell 2007). To determine if model performance varied between a model fit only to $D_{25\%}$ or cumulative flight throughout the year, the target degree-days for $D_{25\%}$ from the log-logistic distribution were used to calculate predicted dates of flight

in the validation dataset, and CCC was calculated for predicted and observed dates of $D_{25\%}$.

Results

Monitoring Moth Flights. Fewer than 25 moths were captured in black light traps in 10 of 83 possible site-years, so data from those site-years were excluded from analysis. Median numbers from the remaining 73 site-years ranged from 577 to 1,318 moths (Table 1). Captures occurred between 8 June to 8 September, but most were caught in July, and cumulative proportions followed sigmoid distributions overall (Figure 1). Average dates when cumulative captures first exceeded $D_{25\%}$, the recommended level for onset of field scouting, progressed northward from 11 July at Clay Center to 18 July at Concord (Table 1). However, $D_{25\%}$ among years at each site varied by 3–4 wk (Figure 1).

Model Development. Grid search of candidate starting days and lower and upper temperature thresholds (i.e., parameters with the highest CCC for each calculation method (Figure 2)) indicated that agreement between observed and predicted $D_{25\%}$ was greatest ($CCC =$

Figure 2. Concordance correlation coefficients (CCCs) for alternative degree-day models, calculated with two methods, and combinations of alternative starting dates, upper and lower development thresholds. Each panel was initially linearly interpolated from 1591 CCCs for each lower and upper threshold combination. Values for models with upper thresholds above 30°C are excluded from the graphs, as no change in CCC was visible between 30 and 43.33°C (i.e., no upper threshold). “O” indicates the highest CCC for revised models using simple and sine wave calculation methods.

0.880) with the simple degree-day calculation method with a starting day of 1 March (day 60), a lower threshold of 3.3°C ($\pm$ 95% CI: 0.02), and an upper threshold of 23.9°C ($\pm$ 10.6). Average degree-days at $D_{25\%}$ with this model was 1,461 degree-days °C ($\pm$ 23.2). Agreement was equivalent for the parameters with highest agreement for the half-day sine wave method (CCC = 0.879) with a starting day of 1 January (day 1), a lower threshold of 5.0°C ($\pm$ 2.3), and an upper threshold of 22.8°C ($\pm$ 1.2). Average degree-

days at $D_{25\%}$ with this half-day sine wave model was 1,256 degree-days °C ($\pm$ 19.2). Compared with the original Ahmad (1979) model, agreement using both degree-day calculation methods increased as starting days were moved from May to March, and lower thresholds were lowered below 10°C excluding May (Figure 2). Agreement for upper thresholds did not vary significantly between 43.3°C (no upper threshold) to 30°C and was highest between 23 to 25°C (Figure 2).

Figure 3. Observed days of 25% flight versus days predicted by three phenology models: the Ahmad (1979) model for (a) development and (b) validation datasets; the simple degree-day model for (c) development and (d) validation datasets; and sine wave model for (e) development and (f) validation datasets. Locations are represented by: (●) Aurora, (○) Clay Center, (▼) Concord, and (Δ) North Platte. Solid lines indicate perfect agreement (observed date equals predicted date). Dashed lines are least squares regression lines that indicate deviations from agreement. Overall agreement is characterized by concordance correlation coefficients (CCC), which depend on component measures of precision (Pearson's correlation coefficient, r) and accuracy (A), as defined in text.

Model Validation. Agreement between predicted and observed $D_{25\%}$ in the independent validation dataset was lower than observed with each of the three models in the development dataset (Figure 3). Performance of the simple degree-day model was best overall, and its CCC decreased the least in comparison with performance with the development dataset (from 0.880 to 0.821, Figure 3, c vs. d). The sine-wave model was more accurate than the Ahmad (1979) model ($A = 0.977$ vs. 0.895, Figure 3f vs. 3b), but the sine-wave model was less precise ($r = 0.672$ vs. 0.757) due to one extreme year at the Concord site.

Superiority of the simple degree day model was further evident in differences between matching predicted and ob-

served flight dates (Table 3). Predicted flight days from the simple degree day model were an average of 1.4 d late, but standard deviations and ranges in errors were smaller than with the other two models.

Seasonal Flight Distributions. The simple degreeday model's start date and lower and upper thresholds were used to create the time scale to evaluate seasonal flight distributions. Compiled cumulative flight patterns for the development dataset were again sigmoidal (Figure 4a), as was evident in the original calendar time scale (Figure 1). Fit of the log-logistic distribution was superior to fits of the logistic and Weibull distributions (Figure 4b). Estimated degree-days at $D_{25\%}$ based on the log-logistic distribution (Table 4)

Table 3. Summary statistics for predicted_observed days when 25% flight by *S. albicosta* occurred among 36 site-years in the validation dataset, using the original Ahmad (1979) phenology model, and revised models with simple and sine wave degree-day calculation methods

Model	Mean	SD	Min.	Max
Ahmad ^a	3.1	4.6	-7	12
Best simple ^b	1.4	3.8	-7	7
Best sine-wave ^c	-0.3	5.5	-24	6

a. Starting day = 1 May (= day 121), lower threshold = 10°C, no upper threshold, DD total = 733°C degree days.

b. Starting day = 1 March (= day 60), lower threshold = 3.3°C, upper threshold = 23.9°C, DD total = 1,461°C degree days.

c. Starting day = 1 January (= day 1), lower threshold = 5.0°C, upper threshold = 22.8°C, DD total = 1,256°C degree days.

were not significantly different from the estimate derived from the individual $D_{25\%}$ flight dates in the model development step (1,461; 95% CI: 1,438–1,484°C degree-days), as judged by overlap of the two estimates' 95% confidence intervals. Comparisons of CCCs for predicted and observed $D_{25\%}$ in the development and validation datasets were 0.858 and 0.844, respectively (Figure 5). Mean difference (predicted_observed days) using the distributionbased model was -0.11 d, with standard deviation of 3.7 d and range of -9 to 6 d, similar to errors with the simple model fit to the development dataset.

Discussion

Model analysis with CCC demonstrated that the March start date model using simple-degree days was more precise and accurate than the Ahmad (1979) model and had a high amount of agreement in both model development and validation datasets. We also demonstrated that there was not a significant difference between target degree-days calculated from either average degree-days at $D_{25\%}$ or from modeling the entire annual flight distribution; agreement varied relatively little between the two methods of deriving target degree-days under the chosen degree-day calculation method (Figures 3c & 3d and 5). Because of the improved performance over the Ahmad (1979) model, we recommend beginning simple degree-day accumulation 1 March while using a lower threshold of 3.3°C and an upper threshold of 23.9°C to predict $D_{25\%}$ for *S. albicosta* annual adult flight at 1,432 degree-days °C. Degree-days corresponding to other levels of cumulative annual flight can be calculated with equation [3] as shown in Table 4.

Results of the comparison of degree-day calculation methods in the development dataset were surprising because the sine-wave method was expected to account for spring temperatures better than the simple method (Allen 1976). In this case, there was relatively little difference in CCCs between the simple and sine-wave calculation meth-

ods for most models. The lack of differences may be due to moderating effects of soil on air temperatures, which has been previously documented to reduce amplitudes of soil temperatures and their effects on other noctuids like *S. albicosta* that overwinter in the soil (Campbell and Norman 1998, Morey et al. 2012). Soil degree-days were determined for *S. albicosta* by Antonelli (1974). Historically, soil degree-days have not been used because Antonelli (1974) did not specify the calculation method used for estimating *S. albicosta* soil degree-days, and soil temperature data are not usually readily available in many areas (Ahmad 1979). Our results indicate differences in air temperature degree-days as calculated with simple and sine-wave methods may not result in a biologically significant difference in soil degree-days as experienced by *S. albicosta* in soil.

Model performance increased when the start dates from January to April were used instead of May; using a May start date consistently produced the lowest CCC values (Figure 2). This may be indicative of late winter or early spring temperatures playing a major role in the phenology of *S. albicosta* and possibly cues that trigger the cessation of overwintering behavior (Hanson et al. 2013). Use of the earlier March start date may also make the new model more applicable to states south of Nebraska where significant temperature accumulation can occur before 1 May. This effect may not be as pronounced in areas north or northeast of Nebraska, but significant degree-day accumulation could be occurring between March and May during some years in these northern areas. By contrast, we also found that moving the model start date too early in the year can have disadvantages. The sine-wave model with the highest CCC in the development dataset had a January start date and predicted moth flight relatively well. However, the sine-wave model did not perform as well in the validation dataset, which appears to be due to one outlier year during 2009 at Concord when observed $D_{25\%}$ occurred 24 d later than predicted (Figure 3f). During this year, temperatures in January were much warmer than other years and allowed 336 degree-days °C to accumulate by 1 February. In other years, accumulations were usually <30 degree-days °C by 1 February. The abnormally warm January temperatures may not have contributed to development or breaking diapause so early in the year, which may explain why observed flight occurred later in the year than predicted.

Ahmad (1979) arbitrarily chose lower threshold of 10°C based on the *Zea mays* degree-day model, but our analysis shows that the degree-day model of a corn pest such as *S. albicosta* may not be similar to that of its host plant. With a May start date, models with a lower threshold near 10°C showed reasonable agreement, but in earlier months, lower thresholds below 10°C led to higher agreement (Figure 2). Antonelli (1974) determined the lower threshold of *S. albicosta* was 4.4°C when using soil temperatures at ~10cm depth. Other noctuids with known developmental thresholds include *Agrotis ipsilon* with a lower threshold of 10.5°C, *Papaipema nebris* with a lower threshold 5.0°C, and *Helicoverpa zea* with a lower threshold of 12.3°C when reared on corn and 7.7°C on cotton (Butler 1976, Luckmann

Figure 4. Cumulative distributions of moths captured ($n = 52,549$) in the development dataset across all years plotted against cumulative degree days based on the best simple degree-day model for: **(a)** cumulative percent moths captured each day (dots) within each year (individual years not distinguished for clarity) and the predicted log-logistic model (line), **(b)** comparisons of logistic, log-logistic, and Weibull-fit distributions with logit transformed cumulative percentages. The best fit log-logistic model ($\mu = 7.315$ and $s = 0.044$) is superposed over observed daily flight percentages in panel a.

et al. 1976, Rice and Davis 2010). The range of lower thresholds measured for those noctuids is higher than the lower threshold of 3.3°C we propose for *S. albicosta* when using air temperature. Both our proposed lower threshold and the soil-temperature threshold proposed by Antonelli (1974) are lower than other soil-dwelling noctuids. However, caution should also be used in interpreting the upper and lower developmental thresholds in our model while comparing with other species. As our model was not developed from lab-reared specimens where actual experienced temperatures

were measured, the 3.3°C lower threshold is likely to account for effects of microclimate and physiological responses of *S. albicosta* to soil temperatures.

When calculating degree-days using our model, care should be taken to calculate simple degree-days as specified in our methods. Simple degree-days have been calculated differently by some authors who set daily high temperatures or daily low temperatures to the upper or lower threshold if exceeded, respectively, before determining the mean temperature and subtracting the lower threshold (re-

Table 4. Estimated mean (and 95% confidence limits) times in °C and °F degree-days when arbitrary levels of percent annual flight by *S. albicosta* would occur, as estimated with a log-logistic flight distribution model fit to the composite flight distribution from the model development dataset

Level of flight (%)	°C degree-days	°C (95% CI)	°F degree-days	°F (95% CI)
5	1,321	(1,024–1,703)	2,377	(1,843–3,066)
10	1,364	(1,193–1,561)	2,456	(2,147–2,809)
25	1,432	(1,342–1,527)	2,577	(2,416–2,749)
50	1,502	(1,432–1,577)	2,704	(2,577–2,838)
75	1,577	(1,478–1,682)	2,838	(2,660–3,027)
90	1,654	(1,446–1,892)	2,977	(2,603–3,406)
95	1,709	(1,325–2,204)	3,077	(2,385–3,968)

Centigrade degree-days calculated from log-logistic distribution with $\mu = 7.315$ (SE = 0.003) and $s = 0.044$ (SE = 0.002), and converted to Fahrenheit by $DD_F = DD_C \times 1.8$ (Preuss 1983).

Degree-days calculated with best simple degree-day model, starting day = 1 March (= day 60), lower threshold = 3.3°C, and upper threshold = 23.9°C.

viewed by McMaster and Wilhelm 1997). While neither calculation method has a clear advantage over the other, using one specific simple-degree day calculation to build and test a model, and using the other method during implementation by growers can lead to significant under- or overprediction of a phenological event (McMaster and Wilhelm 1997). As calculated in this analysis, the Ahmad (1979) model averaged daily high and low temperatures first, and then set the average equal to the lower threshold when required. If a different calculation method was mistakenly used in *S. albicosta* management programs in the past, this may be an additional reason why the Ahmad (1979) model was not performing well; thus, anyone previously using simple degree-day models should verify they are using the appropriate calculation method.

A common problem in the literature assessing model error is that indices of overall agreement are not considered, or metrics (e.g., r^2 or coefficient of determination) are improperly used that do not depict agreement when regressing observed and predicted variables (Lin 1989, Liao 2003, Tedeschi 2006). Meek et al. (2009) demonstrated that agreement indices such as CCC are underutilized in agronomic modeling. Our results also underscore the importance of measuring overall agreement rather than only accuracy or precision, respectively. Ahmad's (1979) use of mean error alone would account for accuracy, but does not account for a difference in precision, which is apparent when the mean errors are similar (Lin 1989). For instance, Ahmad (1979) compared the mean error of models with start dates in April and May and found no significant difference in mean error between start dates. The Ahmad (1979) model did show a high amount of accuracy, but lower precision and overall agreement in our validation dataset (Figure 4a). Many of the model parameters we tested for agreement led to better model prediction than a May start date using the 10°C lower threshold, which shows that the Ahmad (1979) model parameters would not have been selected within our analysis (Figure 2).

Figure 5. Observed versus predicted 25% flight days and measures of agreement CCCs for target degree-days from the log-logistic distribution model (1,432°C) at (a) development and (b) validation sites. Degree-days calculated as simple degree-days, starting day = 1 March (= day 60), lower threshold = 3.3°C, and upper threshold = 23.9°C. Locations are represented by: (●) Aurora, (○) Clay Center, (▼) Concord, and (△) North Platte. Solid lines indicate perfect agreement (observed date equals predicted date). Dashed lines are least squares regression lines that indicate deviations from agreement. Overall agreement is characterized by concordance correlation coefficients (CCC), which depend on component measures of precision (Pearson's correlation coefficient, r) and accuracy (A), as defined in text.

Our revised model should be validated in other states to determine if it will be applicable outside of Nebraska or with other sampling methods such as pheromone traps. Blacklight trap data are sparse in other areas due to the maintenance and the cost to run the traps, which makes them difficult to use for widespread scouting (Mahrt et al. 1987). Pheromone traps are commonly used to record cumulative moth flights, but are limited to the capture of *S. albicosta* males. However, we used blacklight data in this analysis as a later date of peak flight can occur if estimated with pheromone traps than blacklight traps; in part, this may be the result of females emerging earlier than males (Mahrt et al. 1987, Merrill et al. 2011). Because *S. albicosta* adults are detected earlier with blacklight traps, we expect our degree-day model based on blacklight data will provide forewarning for when pheromone traps should especially be monitored to determine if adults are present in addition to scouting for egg masses. Factors other than

temperature that vary locally or regionally (e.g., storms or prevailing winds) could also influence when individuals are captured in an area due to population movement (Merrill et al. 2011). Factors such as this would not be accounted for by a degree-day model. We did not include predictors other than degree-days because we wanted to provide a simple-to-use model for growers and crop consultants, as more complex phenology models are often not adopted for applied use (Pruess 1983).

Efficient scouting is foundational to a successful integrated pest management program for *S. albicosta* (Paula-Moraes et al. 2011, 2013). Therefore, using this new simple model, we suggest that crop professionals scout fields for *S. albicosta* between 1,432 and 1,502 degree-days (2,577 to 2,704 degree-days °F) when 25 and 50% cumulative flight are predicted to occur, respectively. The model proposed in this study improved predictions of cumulative *S. albicosta* moth flights and should also improve timing and efficiency of field scouting. Following additional validation in other states, the revised model may also be applicable to a wider geographic range than the previous model.

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References cited

- Ahmad, T. R. 1979.** Comparison of heat unit accumulation methods for predicting European corn borer and western bean cutworm moth flights. M.S. thesis, University of Nebraska, Lincoln, NE.
- Allen, J. C. 1976.** A modified sine wave method for calculating degree days. *Environ. Entomol.* 5: 388–396.
- Antonelli, A. L. 1974.** Resistance of *Phaseolus vulgaris* cultivars to western bean cutworm, *Loxagrotis albicosta* (Smith), with notes on the bionomics and culture of the cutworm. Ph.D. dissertation, University of Idaho, Moscow, ID.
- Appel, L. L., R. J. Wright, and J. B. Campbell. 1993.** Economic injury levels for western bean cutworm, *Loxagrotis albicosta* (Smith) (Lepidoptera: Noctuidae), larvae in field corn. *J. Kans. Entomol. Soc.* 66: 434–438.
- Broatch, J. S., L. M. Dosdall, G. W. Clayton, K. N. Harker, and R. C. Yang. 2006.** Using degree-day and logistic models to predict emergence patterns and seasonal flights of the cabbage maggot and seed corn maggot (Diptera: Anthomyiidae) in canola. *Environ. Entomol.* 35: 1166–1177.
- Burnham, K. P., and D. R. Anderson. 1998.** Model selection and multimodel inference: A practical information-theoretic approach, 2nd ed. Springer-Verlag, New York, NY.
- Butler, G. D., Jr. 1976.** Bollworm: development in relation to temperature and larval food. *Environ. Entomol.* 5: 520–522.
- Campbell, G. S., and J. M. Norman. 1998.** An introduction of environmental biophysics, 2nd ed. Springer-Verlag, New York, NY.
- Cook, R. D., and S. Weisberg. 2004.** Applied regression including computing and graphics. Software and delta method addon accessed at <http://stat.umn.edu/arc/> (accessed 1 October 2014).
- Eichenseer, H., R. Strohbehn, and J. Burks. 2008.** Frequency and severity of western bean cutworm (Lepidoptera: Noctuidae) ear damage in transgenic corn hybrids expressing different *Bacillus thuringiensis* cry toxins. *J. Econ. Entomol.* 101: 555–563.
- Hagen, A. F. 1962.** The biology and control of the western bean cutworm in dent corn in Nebraska. *J. Econ. Entomol.* 55: 628–631.
- Hanson, A. A., S. Paula-Moraes, T. E. Hunt, and W. D. Hutchison. 2013.** Supercooling point of western bean cutworm (Lepidoptera: Noctuidae) collected in eastern Nebraska. *Great Lakes Entomol.* 46: 216–224.
- Horner, J. L. 1948.** The cutworm *Loxagrotis albicosta* on beans. *J. Econ. Entomol.* 41: 631–635.
- Holtzer, T. O. 1983.** Distribution of western bean cutworm eggs among short-, mid-, and long-season corn hybrids planted on different dates. *Environ. Entomol.* 12: 1375–1379.
- (HPRCC) High Plains Regional Climate Center. 2010.** Observation stations. <http://www.hprcc.unl.edu/stations/> (accessed 10 June 2010).
- Liao, J. Z. 2003.** An improved concordance correlation coefficient. *Pharm. Stat.* 2: 253–261.
- Lin, L. 1989.** A concordance correlation coefficient to evaluate reproducibility. *Biometrics* 45: 255–268.
- Lin, L., A. S. Hedayat, B. Sinha, and M. Yang. 2002.** Statistical methods in assessing agreement: Models, issues, and tools. *J. Am. Stat. Assoc.* 97: 257–270.
- Luckmann, W. H., J. T. Shaw, D. W. Sherrod, and W. G. Ruesink. 1976.** Developmental rate of the black cutworm. *J. Econ. Entomol.* 69: 386–388.
- Mahrt, G. G., R. L. Stoltz, C. C. Blickenstaff, and T. O. Holtzer. 1987.** Comparisons between blacklight and pheromone traps for monitoring the western bean cutworm (Lepidoptera: Noctuidae) in South Central Idaho. *J. Econ. Entomol.* 80: 242–247.
- McMaster, G. S. and W. W. Wilhelm. 1997.** Growing degree-days: One equation, two interpretations. *Agric. For. Meteorol.* 87: 291–300.
- Meek, D. W., T. A. Howell, and C. J. Phene. 2009.** Concordance correlation for model performance assessment: An example with reference evapotranspiration observations. *Agron. J.* 101: 1012–1018.

- Merrill, S. C., S. M. Walter, F. B. Peairs, and J. A. Hoeting. 2011. Spatial variability of western bean cutworm populations in irrigated corn. *Environ. Entomol.* 40: 654–660.
- Michel, A. P., C. H. Krupke, T. S. Baute, and C. D. Difonzo. 2010. Ecology and management of the western bean cutworm (Lepidoptera: Noctuidae) in Corn and Dry Beans. *J. Integr. Pest Manage.* 1: A1–A10.
- Miller, N. J., D. L. Dorhout, M. E. Rice, and T. W. Sappington. 2009. Mitochondrial DNA variation and range expansion in western bean cutworm (Lepidoptera: Noctuidae): No evidence for a recent population bottleneck. *Environ. Entomol.* 38: 274–280.
- Morey, A. C., W. D. Hutchison, R. C. Venette, and E. C. Burkness. 2012. Cold hardiness of *Helicoverpa zea* (Lepidoptera: Noctuidae) pupae. *Environ. Entomol.* 41: 172–179.
- Nam, Y., and W. I. Choi. 2014. An empirical predictive model for spring emergence of *Thecodiplosis japonensis* (Diptera: Cecidomyiidae): model construction and validation on the basis of 25 years of field observation data. *J. Econ. Entomol.* 107: 1136–1141.
- Nam, Y., S. Koh, D. Won, J. Kim, and W. I. Choi. 2013. An empirical predictive model for the flight period of *Platypus koryoensis* (Coleoptera: Platypodinae). *Appl. Entomol. Zool.* 48: 515–224.
- O'Rourke, P. K., and W. D. Hutchison. 2000. First report of the western bean cutworm *Richia albicosta* (Smith) (Lepidoptera: Noctuidae), in Minnesota corn. *J. Agric. Urban Entomol.* 17: 213–217.
- Paula-Moraes, S., E. C. Burkness, T. E. Hunt, R. J. Wright, G. L. Hein, and W. D. Hutchison. 2011. Cost-effective binomial sequential sampling of western bean cutworm, *Striacosta albicosta* (Lepidoptera: Noctuidae), egg masses in corn. *J. Econ. Entomol.* 104: 1900–1908.
- Paula-Moraes, S., T. E. Hunt, R. J. Wright, G. L. Hein, and E. E. Blankenship. 2013. Western bean cutworm survival and the development of economic injury levels and economic thresholds in field corn. *J. Econ. Entomol.* 106: 1274–1285.
- Philips, C. R., D. A. Herbert, T. P. Kuhar, D. D. Reisig, and E. A. Roberts. 2012. Using degree-days to predict ce-
real leaf beetle (Coleoptera: Chrysomelidae) egg and larval population peaks. *Environ. Entomol.* 41: 761–767.
- Picard, R. R. and R. D. Cook. 1984. Cross-validation of regression models. *J. Am. Stat. Assoc.* 70: 575–583.
- Piñeiro, G., S. Perelman, J. P. Guerschman, and J. M. Paruelo. 2008. How to evaluate models: observed vs. predicted or predicted vs. observed? *Ecol. Model.* 216: 316–322.
- Powell, L. A. 2007. Approximating variance of demographic parameters using the delta method: A reference for avian biologists. *The Condor* 109: 949–954.
- Pruess, K. P. 1983. Day-degree methods for pest management. *Environ. Entomol.* 12: 613–619.
- PSU Pestwatch. 2014. Pennsylvania State University Pest Watch. <http://www.pestwatch.psu.edu/sweetcorn/tool/tool.html> (accessed 15 March 2014)
- Régnière, J. 1984. A method of describing and using variability in development rates for the simulation of insect phenology. *Can. Entomol.* 116: 1367–1376.
- Rice, M. E. 2000. Western bean cutworm hits northwest Iowa, p. 163. Integrated Crop Management IC-484(22). Iowa State University Extension, Ames, IA. <http://www.ipm.iastate.edu/ipm/icm/2000/9-18-2000/wbcw.html> (accessed 30 April 2015).
- Rice, M. E., and P. Davis. 2010. Stalk borer (Lepidoptera: Noctuidae) ecology and integrated pest management in corn. *J. Integr. Pest Manage.* 1: C1–C6.
- SAS Institute Inc. 2014. Version 9.3. SAS Institute. Cary, NC.
- Seymour, R. C., G. L. Hein, and R. J. Wright. 2010. Western bean cutworm in corn and dry beans. University of Nebraska-Lincoln Extension. <http://www.ianrpubs.unl.edu/pages/publicationD.jsp?publicationId=1287> (accessed 30 April 2015).
- Tedeschi, L. O. 2006. Assessment of the adequacy of mathematical models. *Agric. Syst.* 89: 225–247.
- Tein, J. and D. P. MacKinnon. 2003. Estimating mediated effects with survival data. pp. 405–412. In H. Yanai, A. Okada, K. Shigemasa, Y. Kano, and J. J. Meulman (eds.), *New Developments in Psychometrics* (Part 5). Springer, Japan; doi: 10.1007/978-4-431-66996-8_46