Model of *Cryptolestes ferrugineus* Flight Activity Outside Commercial Steel Grain Bins in Central Oklahoma

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ABSTRACT Unbaited sticky traps were placed on ropes in the four cardinal directions and at different heights on the outside of commercial steel bins containing stored wheat. Weekly trap catches of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens), were examined. The number of traps per steel bin varied due to differences in dimensions, and three height classes were established, but there was no significant difference in trap catches of *C. ferrugineus* among height classes. Significant yearly and between-steel bin variation was found, and these effects were removed before using a response surface regression analysis to determine how well two time variables (daylength and day number) and three weather variables (minimum and maximum temperature and precipitation) could explain the seasonal variation in *C. ferrugineus* flight activity. These variables were used in separate analyses of *C. ferrugineus* trap catches in the four cardinal directions and from the three height classes (12 separate analyses). The most robust model fit was obtained when using a subset representing 208 *C. ferrugineus* trap catches from the northern side at height class 3 (traps s placed at least three-quarters of bin height). The full model of the two time variables and three weather variables explained 48% of the variance in this subset of trap catches, whereas a model based on weekly means of daylength and minimum and maximum air temperatures explained 40% of the total variance in *C. ferrugineus* trap catches. The relative trap catch response to daylength and minimum and maximum air temperatures was evaluated. High beetle flight activity around grain bins may indicate a high risk of insect infestation of stored wheat, and the presented model can therefore be used to determine time periods with high risk of beetle immigration into commercial steel bins.

KEY WORDS decision support tools, modeling, Oklahoma, stored-product beetles

SURVEYS IN NORTH AMERICA have documented the widespread and frequent occurrence of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Laemophoeidae) in cereal storage facilities (Barak and Harein 1981; Storey et al. 1983; Cuperus et al. 1986, 1990; Arbogast and Mullen 1988; Hagstrum 1989; Subramanyam et al. 1993; Dowdy and McGaughey 1994, 1998; Hagstrum et al. 1994; Vela-Coiffier et al. 1997). *C. ferrugineus* is an external-feeding pest on stored grain that develops poorly on intact undamaged kernels, and the eggs are laid externally in small crevices of the grain (Smith 1965). Although *C. ferrugineus* only causes minor damage to sound wheat, its presence may trigger price discounts at sale due to the special category "infested" applied during grading when two or more live insects damaging to wheat are found in grading samples (http://www.usda.gov/gipsa/reference-library/standards/standards. htm).

Probe traps have been recommended for detection of *C. ferrugineus* and other insect pests in stored grain, because the insects tend to occur earlier in probe traps compared with insect counts from monitoring on the basis of grain samples (Wright and Hagstrum 1990). Several studies have described the potential use of baited (White and Loschiavo 1986, Fargo et al. 1994, Plarre 1996) and unbaited (Hagstrum et al. 1998, and references therein) probe trap catches of beetles as a decision support tool for estimating insect populations in stored grain. However, as pointed out in several studies (Vela-Coiffier et al. 1997, Hagstrum et al. 1998), it is difficult to estimate absolute insect density from probe trap catches because there are many interacting factors that affect the relative performance of the probe traps, such as trap design, grain temperature, trapping duration, insect density, trap placement, and insect species. The difficulties related to interpretation of probe trap catch suggest that probe trap based-models may be difficult to implement as reliable decision support tools.

Although a pheromone of *C. ferrugineus* has been identified (Wong et al. 1983), a synthetic pheromone

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lure is not commercially available (Phillips et al. 2000). *C. ferrugineus* is considered a good flyer and has been intercepted in considerable numbers in unbaited sticky traps that were placed on the outside (Dowdy and McGaughey 1994, 1998; Vela-Coiffier et al. 1997) or in the headspace (Hagstrum et al. 1994) of grain storage facilities, but these studies suggest only a weak correlation between numbers of beetles caught in unbaited sticky traps and individuals in the grain. Instead of trying to estimate population sizes or action thresholds for insect pests inside grain bins, a different and considerably more modest objective would be to use a combination of time and weather variables to model seasonal variation in beetle flight activity on the outside of grain elevators. Seasonal conditions that favor beetle flight activity would then indicate that the stored wheat is at high risk for insect infestation. This approach seems of relevance because studies (e.g., Hagstrum et al. 1998) have indicated that wheat is generally uninfested as it goes into storage. Thus, initial infestations of wheat in grain bins are likely caused by a combination of the following factors: 1) loading of wheat into grain bins containing residual insect populations due to inappropriate prestorage sanitation, 2) infestation during movement/cooling of wheat because of inappropriate sanitation of conveyor system (this is only a potential source of infestation in concrete silos, because wheat in commercial steel bins is rarely moved, 3) infestation after mixing with previously infested wheat brought into the bin after initial loading, and 4) immigration of flying insects through ventilation ducts and other openings to the outside. Hagstrum (1989) and Dowdy and McGaughey (1994) showed that newly harvested wheat was infested by *C. ferrugineus* within the first week after storage, and Hagstrum (1989) found that highest numbers of beetles were sampled from the top layer, which suggests that this storage pest immigrated by flight into the grain bins.

As pointed out by Dowdy and McGaughey (1994, 1998), grain elevator managers need information that allows predictions of insect problems in the near future to optimize their management strategies. More knowledge about the influence of weather conditions on seasonal flight activity patterns of stored-product insects may be used in development of decision support tools for improved management of stored grain, because time periods with high insect flight activity likely increase the risk of insect immigration into grain bins. For instance, it may be argued that the seasonal flight activity pattern of beetles can affect the decision on when it is most appropriate to fumigate or aerate a grain bin. It is therefore of interest to determine how the seasonal flight activity pattern of *C. ferrugineus* is related to seasonal trends and changes in weather conditions.

In this study, we examined the number of *C. ferrugineus* individuals caught in unbaited sticky traps placed at different heights in the four cardinal directions on the outside of commercial steel bins in 1993, 1994, and 2002. The following topics were addressed: 1) at what height and cardinal direction should an unbaited sticky trap be placed to make the most robust fit of time variables and weather variables to the *C. ferrugineus* flight activity, and 2) which time variables and weather variables provide the most robust model fit of the *C. ferrugineus* flight activity. The model fit was used to outline seasonal weather conditions that trigger fluctuations in *C. ferrugineus* flight activity near commercial steel bins.

Materials and Methods

Steel Bins and Traps. In central Oklahoma, unbaited sticky traps (Phercon II, Trécé Inc., Salinas, CA) were attached to ropes on the exterior of commercial steel bins in four cardinal directions. The ropes ran through pulleys bolted through the roof eaves for efficient trap replacement. All steel bins contained hard red winter wheat, *Triticum aestivum* (L.), and their relative sizes and capacities are presented in Fig. 1. Unbaited sticky traps were serviced every week and reused up to three times, and although other insects were also caught, this study only concerns the catches of *C. ferrugineus.* Traps were occasionally lost due to high winds and/or rain, but lost traps represented <2% of the installed traps.

Trapping in 1993 and 1994. In both 1993 and 1994, unbaited sticky traps were placed on the outside of two steel bins, one at Crescent (35° N 51′ and 97° W 36′) and one at Kingfisher (35° N 51′ and 97° W 56′). Trapping was initiated during the second week of June and continued for 12–18 consecutive weeks (Fig. 2). Unbaited sticky traps were placed in the four cardinal directions at each of the following heights (numbered 1–5, starting from the ground) (20 traps): ground level, one-quarter bin height, one-half bin height, three-quarters bin height, and outside roof eaves at the top of side walls (Fig. 1). Before loading the grain, the steel bins were swept clean and fumigated with chloropicrin at recommended rates (Cuperus et al. 2002), and loading of grain took place during the first week of July in 1993 and in last week of June in 1994. The cleaning and fumigation was done to rule out that residual insects from the bins were the source of insects trapped on the outside of bins. In 1993, the commercial steel bin in Crescent was only half-full, whereas it was full in 1994. The steel bin in Kingfisher was full in both 1993 and 1994.

Trapping in 2002. All steel bins contained newly harvested wheat, and loading of grain into bins was completed within the first week of June 2002, and weekly trapping was conducted for 11 consecutive weeks (Fig. 2). As in 1993 and 1994, unbaited sticky traps were placed on ropes in the four cardinal directions at ground level, one-quarter bin height, one-half bin height, three-quarters bin height, and outside eaves at the two bins in Marshal (36° N 09′ and 97° W 37′), ground level, one-third bin height, two-thirds bin height, and outside eaves at the bin in Lovell (36° N 03′ and 97° W 38′), and ground level, one-half bin height, and outside eaves at the two bins in Dover (35° N 58′ and 97° W 94′). In 2002, all five steel bins

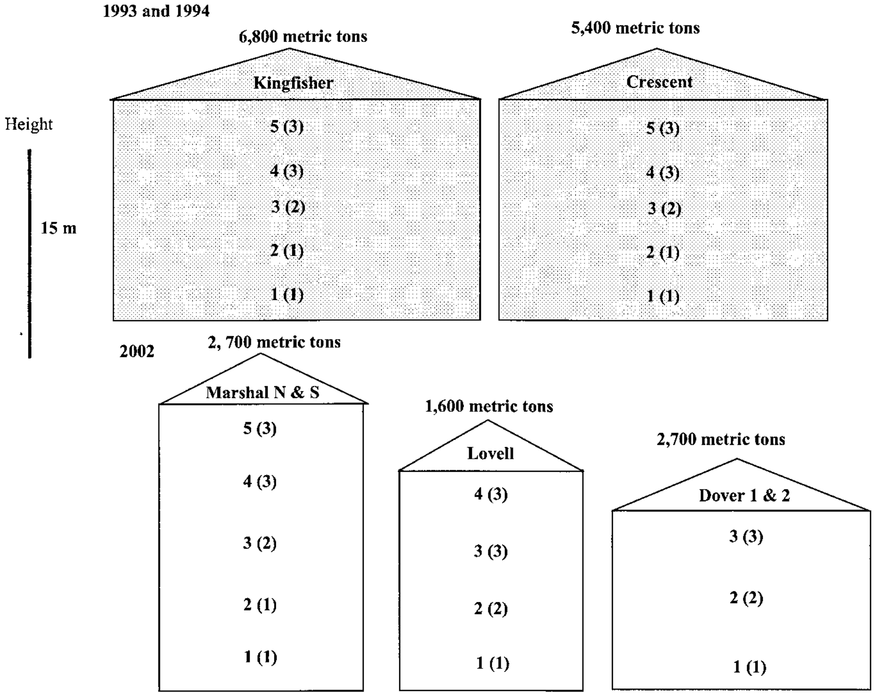

Fig. 1. Relative sizes of commercial steel bins used in this study. The geographical location of the steel bins is outlined in Fig. 2 as well as the trapping period at each steel bin. At each steel bin, traps were placed on exterior ropes in the four cardinal directions. In 1993 and 1994, trapping was conducted at one bin at Kingfisher and one bin at Crescent; in 2002, trapping was conducted at Marshal (two identical bins), Dover (two identical bins), and Lovell (one bin). Due to the difference in heights of the commercial steel bins, we established three height classes (numbers in parentheses), for the comparison of *C. ferrugineus* trap catches between steel bins.

were fumigated with phosphine immediately after being loading of grain.

Statistical Analysis. A repeated measures procedure in PROC MIXED (SAS 8.01) (SAS Institute 1999) was used to analyze the differences in number of beetles captured in traps using the following factors: year, height, and steel bin. The differences between steel bins were analyzed by assigning a number to each trap at each steel bin. For instance, the 16 traps at the steel bin in Lovell were given numbers from 1 to 16, and the

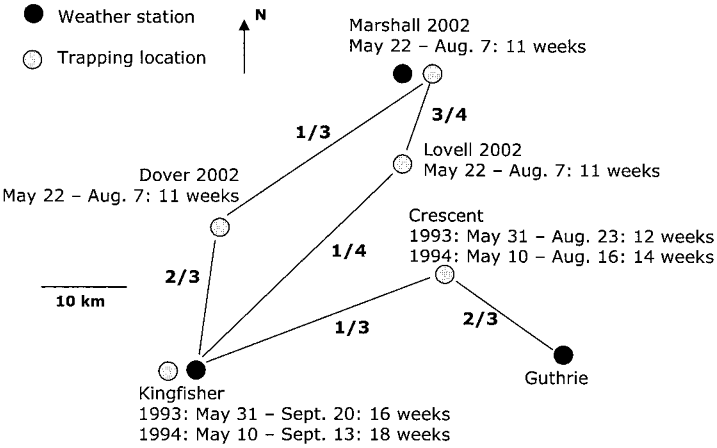

Fig. 2. Relative location of weather stations and trapping locations and trapping period for each of the commercial steel bins included in this study of *C. ferrugineus* trap catches. For trapping locations without weather stations, daily weather data were interpolated on the basis of the linear distance to nearest weather station according to the presented fractions in bold along lines.

same number was given to a trap location (e.g., ground level on the western side) for all 11 wk of trapping. Thus, this numbering enabled an analysis of variation of trap catches within locations over time. For the analysis of *C. ferrugineus* trap catch in 2002, contrasts were outlined for pairwise analysis of the difference in number of beetles captured in traps at the four cardinal directions.

Overall Modeling Approach. The considerable difference in total capacities and heights of steel bins used in this study ensured that the model of *C. ferrugineus* trap catch was representative for most types of commercial steel bins in Oklahoma. However, to be able to make direct comparisons of trap catches from different steel bins, three standardized height classes were established (Fig. 1): 1) traps below one-half of bin height, 2) traps one-half to two-thirds of bin height, and 3) traps placed at least three-quarters of bin height. With three height classes and four cardinal directions, the intent was to select the height class and cardinal direction that gave the best fit of time variables and weather variables to the flight activity of *C. ferrugineus.* Applying the model only to trap catches from one height class and cardinal direction would make it easier for researchers, grain elevator managers, and extension personnel to make future improvements of the model presented, because they would only need to place one unbaited sticky trap at each steel bin.

We decided only to include weather variables that are easily obtainable from local weather stations or sources on the Internet. Thus, weekly means of the following weather variables were included: minimum and maximum air temperature (centigrade), and precipitation (centimeters). Daily climate data were obtained from the meteorological stations in Kingfisher, Guthrie, and Marshal (http://www.mesonet.ou.edu). For the trap catches in Crescent, Lovell, and Dover, weather data were linearly interpolated according to the distance to nearest weather stations (Fig. 2). In addition, two time variables were included in the model: day number, which is the weekly mean of discrete numbers ranging from 1 to 365, and daylength, measured in decimal hours. Daylength was obtained from http://aa.usno.navy.mil/.

Two-Step Modeling. The Response Surface Regression procedure (PROC RSREG) in SAS/STAT (SAS 8.00) (SAS Institute 1999) was used to analyze the relationship among explanatory variables and *C. ferrugineus* trap catches. Further details on the use of this regression procedure are available in Freund and Littell (1991). Weekly *C. ferrugineus* trap catches were log10 $(x + 1)$ transformed before modeling. Initially, we found significant variation in weekly *C. ferrugineus* trap catches among steel bins and years of trapping, so a first step was to conduct a response surface regression analysis of all trap catches by using steel bin and years of trapping as the independent variables. In the first response surface regression analysis the independent variables were dichotomous so that, for instance, a trap catch from the steel bin in Lovell was given a score one for the variables named "Lovell" and "2002," whereas it was given a value of 0 for the other variables ("1993," "1994," "Kingfisher," "Crescent," "Dover," and "Marshal"). The residuals from the first model fit were then used as input data for the second model fit, in which we analyzed the *C. ferrugineus* trap catch response to the three weather variables and two times variables. The second response surface regression analysis was conducted for each height class of trap catches separately and subsequently for each of the four cardinal directions. Because the R^2 value provides information about the explained variability associated with a model fit (Neter et al. 1983), we used this coefficient to determine the height class and cardinal direction to which the best model fit was obtained. Using weekly *C. ferrugineus* trap catches on the northern side and height class 3 provided a higher coefficient of determination than for the other cardinal directions, so this subset of the trap catch data set was selected for further analysis.

Model Evaluation. The robustness of the model fit to *C. ferrugineus* flight activity in height class 3 on the northern side was examined when, in single steps, the explanatory variable that contributed the least to the model fit was removed (lowest F value). The response surface regression model of minimum and maximum air temperatures and daylength as independent variables was considered to provide an acceptable fit. The coefficients generated by the response surface regression analysis are not easily interpreted as they are relative to the independent variables included in the model. Therefore, we developed response surfaces of the predicted flight response of *C. ferrugineus* to combinations of minimum air temperatures from 10 to 30°C and maximum air temperatures from 20 to 40°C at four fixed daylengths (14.59, 14.48, 14.28, and 13.86 h) equivalent to the weekly mean daylengths in weeks 1, 3, 5, and 7 between 20 June and 7 August.

Results

Trap Catches in 1993 and 1994. In both 1993 and 1994, the weekly mean of unbaited sticky trap catches of *C. ferrugineus* in Crescent and Kingfisher started to increase in July and were highest around August (Fig. 3). From the repeated measures analysis of *C. ferrugineus* trap catch, we found no statistical difference among height classes ($F_{2,14} = 1.75; P = 0.209$), whereas there was a significant difference between catches in the four cardinal directions ($F_{3,14} = 8.61; P = 0.002$). Of 190 and 839 *C. ferrugineus* individuals caught in 1993 in Crescent and Kingfisher, respectively, 161 (85%) and 367 (44%) were caught in traps on the northern side. In 1994, only a total of 16 *C. ferrugineus* were caught at Crescent during the 14 wk of trapping, and of these, seven were caught in traps on the western side. In 1994, a total of 28 *C. ferrugineus* were caught at Kingfisher, and most of these beetles (10 *C. ferrugineus*) were caught in traps

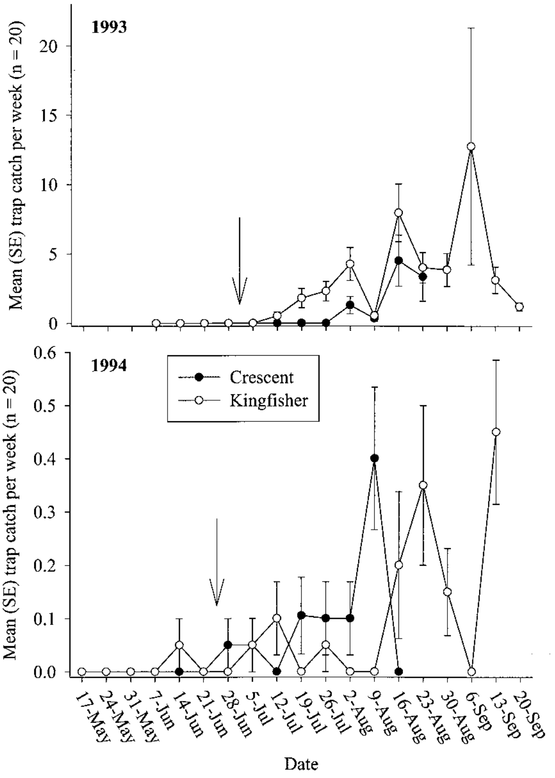

Fig. 3. Weekly means of *C. ferrugineus* trap catches at Kingfisher and Crescent in 1993 and 1994. Each dot represents the mean of 20 trap catches in each week (five heights and four cardinal directions) (Fig. 2). The arrow indicates the week in which the harvested wheat was loaded into the grain bin.

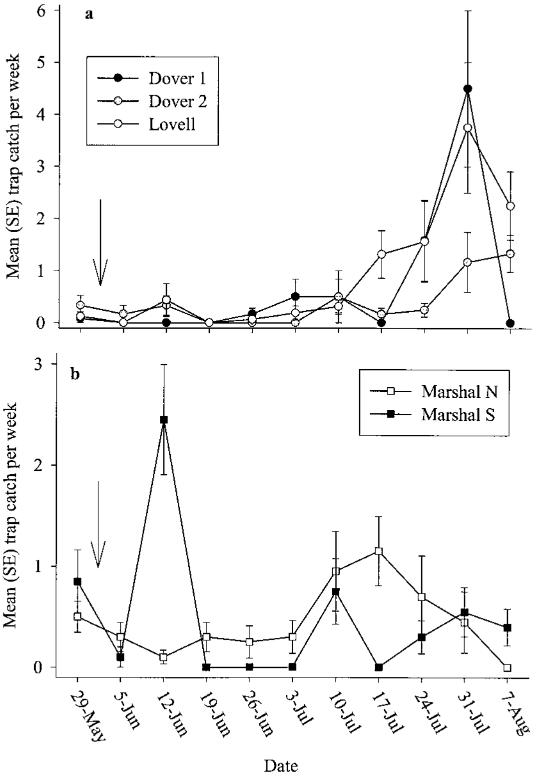

Fig. 4. Weekly means of *C. ferrugineus* trap catches at two commercial steel bins in Dover and one in Lovell, and at two steel bins in Marshal in 2002. Each dot represents the mean of weekly trap catches at different heights and four cardinal directions) (Fig. 2). The arrow indicates the week in which the harvested wheat was loaded into the grain bin.

on the southern side. Thus, there was considerable variation among years regarding the directional pattern of *C. ferrugineus* trap catches. There was a highly significant difference between years ($F_{1,19}$ = 77.47; $P < 0.001$), with trap catches of *C. ferrugineus* being ≈24-fold higher in 1993 compared with 1994 (Fig. 3), and there was a significant difference between the two steel bins ($F_{1,19}$ = 12.72; P = 0.002).

Trap Catches in 2002. The seasonal patterns of weekly mean trap catches of *C. ferrugineus* were similar for Dover 1, 2, and Lovell with the main peak in late July (Fig. 4a). The unbaited sticky traps at the two commercial steel bins in Marshal indicated different seasonal flight activity patterns of *C. ferrugineus* (Fig. 4b). Although the two bins were right next to each other, at the Marshal north bin, the highest mean *C. ferrugineus* trap catch occurred in the first half of July, whereas at the Marshal south steel bin there was a steep increase in mean *C. ferrugineus* trap catch about mid-June. Despite the apparent differences in main seasonal peaks, there was no significant seasonal difference in trap catches among the five steel steel bins ($F_{4,56}$ = 1.14; P = 0.348), nor was there a significant difference among height classes ($F_{2,6}$ = 0.81; P = 0.489). However, there was a highly significant difference in mean *C. ferrugineus* trap catches in the four cardinal directions, with significantly higher catches in unbaited traps on the western side of the steel bins ($F_{3,57}$ = 10.06; $P < 0.001$).

Seasonal Weather. The seasonal means of minimum and maximum air temperatures and precipitation were similar for the three trapping periods in 1993, 1994, and 2002, and there were only minor differences among trapping sites (Table 1). We had no access to data on wind speed or direction for 1993, so such variables could not be included in the model fit. However, data on the prevailing daily wind directions were obtained on-line (http://www.mesonet.ou.edu) for 1994 and 2002 and briefly summarized here. 1) In Kingfisher 1994, highest *C. ferrugineus* mean trap catches were obtained within the time period from 1 August to 13 September (44 d) and in 29 of these days the wind mainly came from the south, nine of the days from the north, and 6 d from the east. 2) In 2002, highest *C. ferrugineus* mean trap catches were obtained within the time period from 10 July to 7 August (29 d), and daily prevailing wind direction in Kingfisher showed that in 20 of these days the wind mainly came from the south, six of the days from the east, 2 d from the north, and 1 d without a prevailing wind direction. 3) In the

Table 1. Weekly mean (SE) weather conditions for the trapping periods in 1993, 1994, and 2002

Location	Year	Days	Weekly mean (SE) temperature (°C)		Precipitation (cm)
			Maximum	Minimum	Mean (SE)
Crescent	1993	112	33.0 (0.4)	20.3 (0.4)	0.304 (0.1)
Kingfisher	1993	112	32.0 (0.4)	19.9 (0.4)	0.267 (0.1)
Crescent	1994	127	32.2 (0.4)	18.8 (0.3)	0.189 (0.1)
Kingfisher	1994	127	33.2 (0.4)	18.46 (0.4)	0.196 (0.1)
Dover	2002	78	32.4 (0.4)	19.1 (0.3)	0.346 (0.1)
Lovell	2002	78	32.1 (0.4)	19.1 (0.3)	0.353 (0.1)
Marshal	2002	78	32.0 (0.4)	19.1 (0.3)	0.357 (0.1)

Daily weather data were obtained from weather stations in Guthrie, Kingfisher, and Marshal, and weather data for Crescent, Dover, and Lovell were interpolated according to distance from nearest weather stations (Fig. 2).

time period from 10 July to 7 August (29 d) 2002, the daily prevailing wind direction in Marshal showed that in 19 of these days the wind mainly came from the south, 9 d from the east, 1 d from the north, and 2 d without a prevailing wind direction. Thus, there was a consistent yearly and geographical pattern with the wind mainly blowing from the south during the time period in which the highest seasonal *C. ferrugineus* mean trap catches were obtained.

Modeling. The model fit of the dichotomus variables accounting for steel bins and years of trapping was used to analyze the entire trap catch data set of 2,069 weekly trap catches and provided a significant model fit ($F = 43.42$, $P < 0.001$, $R^2 = 0.11$). The residuals from this model fit were subsequently analyzed with the two time variables and three weather variables as independent variables to determine the height class that provided the best model fit (based upon the coefficient of determination, R^2): height class 1 (787 trap catches): $R^2 = 0.10$, height class 2 (456 trap catches): $R^2 = 0.15$, and height class 3 (826 trap catches): $R^2 = 0.18$. Subsequently, because of the poor model fit, separate model fits for each of the four cardinal directions were conducted for the trap catches in height class 3: west $R^2 = 0.21$, south $R^2 = 0.22$, east $R^2 = 0.24$, and north $R^2 = 0.48$. Of the entire data set of 2069 trap catches, 208 trap catches belonged to the subset of height class 3 on the northern side of the steel bins, and these trap catches were used for the evaluation of the relative contribution of each of the explanatory variables (Table 2). Excluding day number and precipitation as explanatory variables reduced the explained variance by ≈15% from 0.48 to 0.40. Daylength contributed the most to the model fit, and it alone explained about half of the total variance of the model fit. It was decided to base the model fit on the linear and quadratic responses and the linear combination of three explanatory variables: daylength, and minimum and air maximum temperatures.

Model Evaluation. In the model fit of *C. ferrugineus* trap catches (C), the coefficients for daylength (D), and minimum (t) and air maximum (T) temperatures were as follows:

$$C(D,t,T) = -5.199D - 0.543t + 1.229T + 0.264D^2 - 0.004t^2 - 0.006T^2 + 0.014Dt - 0.081DT + 0.016tT \quad [1]$$

We examined the predicted *C. ferrugineus* trap catches to varying minimum and maximum air temperatures at four fixed daylengths (Fig. 5). The model evaluation demonstrated the importance of including the interactions of independent variables, because, for instance, low minimum and maximum temperatures generated comparatively high predicted trap catches when the days were longer than 14.28 h; but with days shorter than 14.3 h, the highest predicted trap catches were obtained with comparatively high minimum and maximum temperatures.

Table 2. Stepwise exclusion of the least significant variable (lowest *F* value) in the response surface regression analysis

Explanatory variable	Full	Exclusion 1	Exclusion 2[a]	Exclusion 3	Excl 4
Daylength (decimal hour)	7.13***	15.47***	17.08***	23.93***	26.87***
Maximum temperature (°C)	5.54***	5.74***	4.93***	18.11***	
Minimum temperature (°C)	2.86*	2.76*	2.33		
Precipitation (cm)	2.75*	2.27*			
Day no.	2.35*				
R^2	0.48	0.44	0.40	0.38	0.21

The model analysis is based upon a subset of 208 *C. ferrugineus* trap catches from height class 3 (Fig. 2) placed on the northern side of steel bins. For each of the five regression models tested, *F* values show the significance of each variable included, taking into account linear and quadratic terms and linear combinations with other environmental variables. R^2 shows the predictive strength of the regression analysis for each combination of environmental variables.

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

[a] Combination of variables chosen for the model.

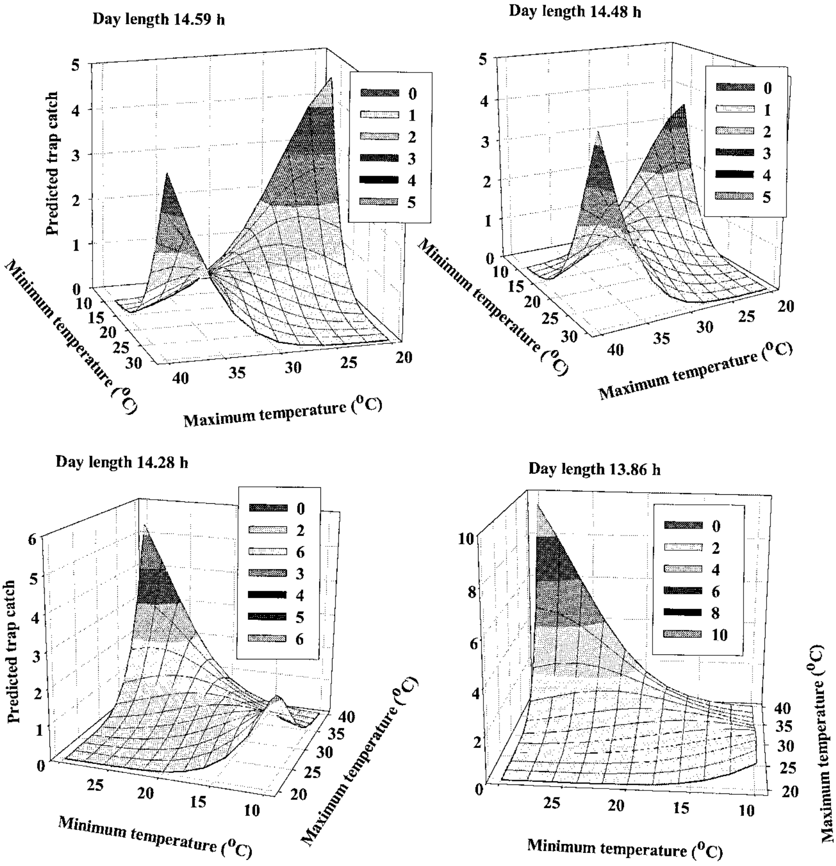

Fig. 5. The predicted model fit of minimum and maximum air temperatures and daylength to weekly means of *C. ferrugineus* trap catches using the model coefficients in equation 1.

Discussion

Our data set showed the following about the seasonal pattern of flight activity of *C. ferrugineus* around commercial steel bins in central Oklahoma. 1) Significant yearly and between-steel bin variation in *C. ferrugineus* trap catches occurred. Dowdy and McGaughey (1998) placed unbaited sticky traps on the outside of four commercial grain elevators in 1993 and 1994 and reported the seasonal trap catches for the four most abundant stored-product beetles caught at each elevator. At one of these grain elevators, *C. ferrugineus* was among the most abundant and similarly to our results, Dowdy and McGaughey (1998) showed that numbers of *C. ferrugineus* caught in traps in 1993 were considerably higher than in 1994. 2) There was a significant difference in *C. ferrugineus* trap catch in the four cardinal directions, but this variation was not consistent for the three years of trapping. Vela-Coiffier et al. (1997) examined beetle catch with unbaited sticky traps on the outside of farm bins from May to September 1991 in Oklahoma and found significantly higher catches on the northern side of farm bins and lower catches on the southern side. Due to the prevailing southern wind direction in both 1994 and 2002, it seems highly unlikely that differences in wind direction played a major role in the seasonal variation in *C. ferrugineus* trap catch. 3) We found no significant difference in trap catch at different height classes, and this result is not consistent with Vela-Coiffier et al. (1997), who placed unbaited sticky traps at four heights on the outside of farm bins and obtained significantly higher beetle catches on the outside of the bin eaves (equivalent to height class 3). The result by Vela-Coiffier et al. (1997) is, however, not directly comparable because they analyzed trap catch for several beetle species, and farm bins are considerably smaller than the commercial steel bins included in this study.

Weather-driven flight activity models are important for understanding insect flight behavior and can be used in the development of risk warning systems and as a decision support tool for predicting when to take action against a given insect pest. This approach seems especially relevant for insect pests with a highly active flight behavior. However, due to the significant differences among cardinal directions, years, and steel bins, we decided to first examine the effect of weather and time variables after initial removal of the variance caused by differences among steel bins and years of trapping. Second, we wanted to identify the best trap placement, so that only data from one trap location would be needed in future improvement of the current model. We found that *C. ferrugineus* trap catches from height class 3 on the northern side provided the most robust fit of the examined time and weather variables, and the modeling indicated the following. 1) Daylength was the explanatory variable that contributed the most to the model fit, and a reduction in daylength of ≈25 min (from 14.28 to 13.86 h) caused almost a two-fold increase in predicted flight activity of *C. ferrugineus* (Fig. 5). This suggests that the flight activity of *C. ferrugineus* follows a general seasonal-dependent flight activity trend. A similar result was obtained by Nansen et al. (2001), who used the same model approach in an analysis of the seasonal flight activity of the larger grain borer, *Prostephanus truncatus* (Horn), in southern Benin, West Africa. 2) Although daylength accounted for most of the seasonal change in flight activity of *C. ferrugineus,* minimum and maximum temperatures had substantial influence on the flight activity. 3) Linear interactions of explanatory variables were very important in the model fit. Minimum and maximum air temperatures are likely correlated, which may inflate variances for parameter estimates and may lead to "wrong" signs of coefficients (Jan Nyrop, personal communication). However, the insect flight response to minimum and maximum temperatures may not be the same and may determined by different physiological processes, and different signs of the model coefficients for minimum and maximum temperatures may actually reflect that.

One possible argument against the use of unbaited sticky traps on the outside of grain bins is that it is not known whether the insects caught in the traps are dispersing from the bins or whether they are immigrating into the bins. Because the steel bins were treated with pesticide either before loading of grain (1993 and 1994) or immediately after loading of grain (2002), it is likely that the majority of the *C. ferrugineus* individuals that were caught in the unbaited sticky traps shortly after loading grain into bins originated from a flying population immigrating into the commercial steel bins. However, it seems reasonable to assume that trap catches during most of the trapping period probably represented individuals both immigrating into the steel bins and some individuals dispersing from the steel bins after infestations were established. For instance, high trap catches at the Marshal south bin in early June are most easily explained as a consequence of *C. ferrugineus* individuals immigrating into the steel bin. Because *C. ferrugineus* density in the steel bins was not accounted for, this study did not allow us to determine to what extent the insect density in the grain was associated with unbaited sticky trap catches.

C. ferrugineus is only one of several insect pests of stored wheat in Oklahoma, and similar weather-driven flight activity models are needed for other stored-product insects, e.g., *Rhyzopertha dominica* (F.), to fully explore the potential of such models as decision support tools for pest management of commercial steel bins. Our model was based on trap catch data that were collected within an area of ≈60 by 60 km, and it is unknown to what extent this model can be used to predict seasonal *C. ferrugineus* flight activity elsewhere in the wheat growing areas of the United States. Model sensitivity to local conditions was shown by Nansen et al. (2001), because their weather-driven flight activity model of *P. truncatus* trap catches in southern Benin was successfully validated with independent trap catch data from the same area, but the same model could not be used to predict *P. truncatus* trap catches in a different agroecological zone 250 km further to the north. Despite the limited geographical distribution of trap catch data used to develop this model, we included data from seven different commercial steel bins of varying total capacities and heights, and trap catch data were collected over three different storage seasons. We are currently in the process of preparing an expanded validation of the weather driven *C. ferrugineus* flight activity model after this 2003 wheat harvest in which grain elevator managers in different parts of Oklahoma will participate and place unbaited sticky traps on the northern side of grain bins to monitor the seasonal flight activity of *C. ferrugineus.*

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