Comparison of Models for Forecasting of Stewart's Disease of Corn in Iowa

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ABSTRACT

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Three forecasting models for Stewart's disease (*Pantoea stewartii* subsp. *stewartii*) of corn (*Zea mays*) were examined for their ability to accurately predict the prevalence of Stewart's disease in Iowa at the county level. The Stevens Model, which is used as a predictor of the early wilt phase of Stewart's disease, the Stevens-Boewe Model, which predicts the late leaf blight phase of Stewart's disease, and the Iowa State Model that is used to predict the prevalence of Stewart's disease, all use mean air temperatures for December, January, and February for a preplant prediction of Stewart's disease risk in a subsequent season. Models were fitted using weighted binary logistic regression with Stewart's disease prevalence data and air temperature data for 1972 to 2003. For each model, the years 1972 to 1999 (n = 786 county-years) were used for model development to obtain parameter coefficients. All three models indicated an increased likelihood for Stewart's disease occurring in growing seasons preceded by warmer winters. Using internal bootstrap validation, the Stevens Model had a maximum error between predicted and calibrated probabilities of 10%, whereas the Stevens-Boewe and Iowa State models had maximum errors of 1% or less. External validation for each model, using air temperature and seed corn inspection data between 2000 and 2003 (n = 154 county-years), indicated that overall accuracy to predict Stewart's disease at the county level was between 62 and 66%. However, both the Stevens and Stevens-Boewe models were overly optimistic in predicting that Stewart's disease would not occur within specific counties, as the sensitivity for these two models was quite low (18 and 43%, respectively). The Iowa State Model was substantially more sensitive (67%). The results of this study suggest that the Iowa State Model has increased predictive ability beyond statewide predictions for estimating the risk of Stewart's disease at the county level in Iowa.

Disease forecasting is an integral component for disease and pest management affecting numerous cropping systems (3,10,28,29). In the Stewart's disease (*Pantoea stewartii* subsp. *stewartii* (syn. *Erwinia stewartii* (Smith) Dye)) of corn (*Zea mays*) pathosystem, for example, forecasting models to predict the severity of the early wilt phase (26), the severity of the late leaf blight phase (2), and the seasonal prevalence in seed corn fields (19) have been developed. These models attempt to predict the amount of initial inoculum (disease risk represented as number of *P. stewartii*–infested corn flea beetles that survived the winter) available in early spring to initiate Stewart's disease epidemics. This risk is often a function of the effect of winter temperatures on survival of corn flea beetle (*Chaetocnema pulicaria* Melsheimer) populations (2–4,19,26).

The Stevens Model (26) was developed by comparing differences in winter air temperatures for years in which Stewart's disease was severe with years when Stewart's was absent or of low severity. Boewe (2) modified Stevens' Model to predict severity of the late leaf blight phase of Stewart's disease using a revised index of mean monthly temperatures; this model became known as the Stevens-Boewe Model (Table 1; 20). The Stevens-Boewe Model was intended to help sweet corn producers prior to planting to be prepared to employ management tactics to minimize Stewart's disease severity. Severe epidemics of Stewart's disease in sweet corn can cause significant yield reductions and also affect quality (8,23,27).

The Stevens-Boewe Model has also been used throughout the U.S. Corn Belt to predict the prevalence of Stewart's disease in seed corn production fields (16,17). Stewart's disease is economically important because the mere presence of Stewart's disease in a seed corn field will invoke phytosanitary measures that severely restrict the overseas export of seed corn from seed corn fields found to have Stewart's disease (12). However, Nutter et al. (19) demonstrated that the Stevens-Boewe Model did not accurately predict the risk of Stewart's disease, as an unacceptable number of false negatives (not predicting a high prevalence of Stewart's disease) were observed. Using prevalence data from the Iowa Department of Agriculture and Land Stewardship (IDALS) seed corn inspection database, these workers reported that a forecasting model based on the number of winter months (December–February) with mean monthly temperatures below a –4.4°C (24°F) temperature threshold better predicted the actual prevalence of Stewart's disease in Iowa than either the Stevens or Stevens-Boewe model (Table 2).

To date, Stewart's disease forecasting in Iowa has emphasized statewide risk (19). In order to provide seed corn producers more site-specific disease risk information, accuracy of the three forecasting models needs to be evaluated at a finer geographic scale. Evaluating the three models at the county level will help producers in making decisions whether to: (i) use an insecticide seed treatment and/or apply foliar insecticides during the growing season (11,13,15,21,22), (ii) choose planting locations with a lower Stewart's disease risk, and (iii) delay date of planting to avoid the overwintering generation of *P. stewartii*–infested corn flea beetles (6,7,13).

Table 1. The Stevens and Stevens-Boewe forecasting models for predicting incidence and severity of Stewart's disease using air temperature data for December, January, and February

Winter temperature index[a]	Stevens Model (seedling wilt phase)	Winter temperature index	Stevens-Boewe Model (late leaf blight phase)
85 to 90°F (–6.2 to –3.3°C)	Nearly absent	<80°F (<–8.8°C)	Trace
90 to 100°F (–3.3 to 2.2°C)	Light to severe	80 to 85°F (–8.8 to –6.2°C)	Light
>100°F (>2.2°C)	Destructive	85 to 90°F (–6.2 to –3.3°C)	Moderate
		90 to 100°F (–3.3 to 2.2°C)	Severe
		>100°F (>2.2°C)	Severe

[a] Winter temperature index is obtained by summing the mean monthly air temperatures for December, January, and February. For example, if the mean temperatures for December, January, and February were 28°F (–2.2°C), 20°F (–6.7°C), and 25°F (–3.9°C), the sum would be 73°F (–12.8°C), and the Stevens Model would predict a "nearly absent" risk of Stewart's disease and the Stevens-Boewe Model would predict a "trace" risk of Stewart's disease.

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The objectives of this study were to: (i) evaluate and compare the Stevens, Stevens-Boewe, and Iowa State Stewarts' disease forecasting models for their ability to accurately predict the prevalence of Stewart's disease at the county level, and (ii) validate all three models for sensitivity (accurately predicting Stewart's disease prevalence given that Stewart's disease was found in a county) and specificity (accurately predicting that no Stewart's disease occurred given that no Stewart's disease was found in a county).

MATERIALS AND METHODS

Iowa seed corn inspection database and Stewart's disease. Seed corn inspection data from IDALS was used for comparison of the Stevens, Stevens-Boewe, and Iowa State models (Tables 1 and 2). We focused on county level disease risk predictions for Stewart's disease prevalence in Iowa using inspection and weather data between 1972 and 2003. Seed corn inspection data were obtained from 70 of the 99 counties in Iowa during this period, but the number of years a county was inspected varied from 1 to 32, with the number of fields inspected varying from 1 to 579. The inbred variety was not known for each field and as such was assumed to differ in potential susceptibility to Stewart's disease. The response variable was prevalence of Stewart's disease, which was calculated as the proportion of seed corn fields in a county found to have Stewart's disease divided by the total number of seed corn fields inspected in that county. For evaluation and comparison of model accuracy, the actual prevalence of Stewart's disease was coded for each county as either 0 (prevalence of Stewart's disease = 0) or 1 (prevalence of Stewart's disease >0). A total of 940 county-years of prevalence and weather data were used for model evaluation and validation.

Model development and validation. Maximum and minimum air temperature data were obtained from the NOAA National Climatic Data Center (obtained online) for each county and year where seed corn inspections had been performed. Missing air temperature data were interpolated from data from counties within the same climate district. In Iowa, there are nine climate districts that represent similar geographic regions (e.g., northwest or north central). The 940 county-years of data were divided into two groups. Data from 1972 to 1999 (n = 786 observations) were used for model development and evaluation. Analysis of these data led Nutter et al. (19) to conclude that the Stevens-Boewe Model had significantly higher false negatives than was acceptable at the state level (Fig. 1). External model validation was performed on independent Stewart's disease prevalence and air temperature data from the years 2000 to 2003 (n = 154 observations). Statewide prevalence of Stewart's disease from 2000 to 2003 was 58.0, 2.8, 4.9, and 8.9% of fields, respectively.

Accuracy in predicting prevalence of Stewart's disease was compared for the Stevens, the Stevens-Boewe, and the Iowa State models using binary logistic regression. Model coefficients were determined using maximum likelihood estimation using the *lrm* function in the *Design* library of R (R 2.1.1, The R Project for Statistical Computing: http://www.r-project.org/) (1,9). In binary logistic regression, the probability that disease prevalence will occur when given a set of values that only take on the values 0 or 1 (no/yes) is:

$$P(Y = \text{Stewart's disease}) = \frac{\exp\left(\sum b_i x_i\right)}{1+\exp\left(\sum b_i x_i\right)} \quad (1)$$

where, x_i represents the predictors in the model and b_i represents the parameters to be estimated (1,9,14). All three forecasting models have categorical predictors (Tables 1 and 2). There were three risk categories for the Stevens Model, five for the Stevens-Boewe Model; and four for the Iowa State Model (2,19,26). Because the number of fields inspected in a given county and year was not uniform across all county-years, all observations were weighted by the number of inspected fields within a county. Preliminary model comparisons were made based on the number of concordant (yes-yes) and discordant (yes-no) pairs, including comparing the probability of concordance (c) and Somers' D_{xy} rank correlation (9). These methods measure the association between predicted probabilities and observed responses. The probability of concordance ranges between 0.5 and 1, with values closer to 1 indicating increased predictive ability. Somers' D_{xy} ranges between 0 and 1, with higher values implying increased predictive ability.

Further model comparisons were made using internal and external validation. Internal bootstrap validation was performed for each model to provide bias-corrected estimates of prediction accuracy since model bias may arise from the overfitting of a model (9). The internal bootstrap procedure randomly resampled with replacement 786 county-year observations from the data used for model development. For each bootstrap run, a new binary logistic regression model was obtained (5,9). The total number of bootstrap samples was

Table 2. Iowa State Model for disease forecasting for the prevalence of Stewart's disease of seed corn in Iowa[a]

Number of months	Predicted risk
0	Negligible
1	Low
2	Moderate
3	High

[a] Iowa State Model examines the mean monthly air temperature for December, January, and February to determine if the monthly mean temperature was ≥ –4.4°C (24°F) and then sums the number of months that were beyond the threshold temperature.

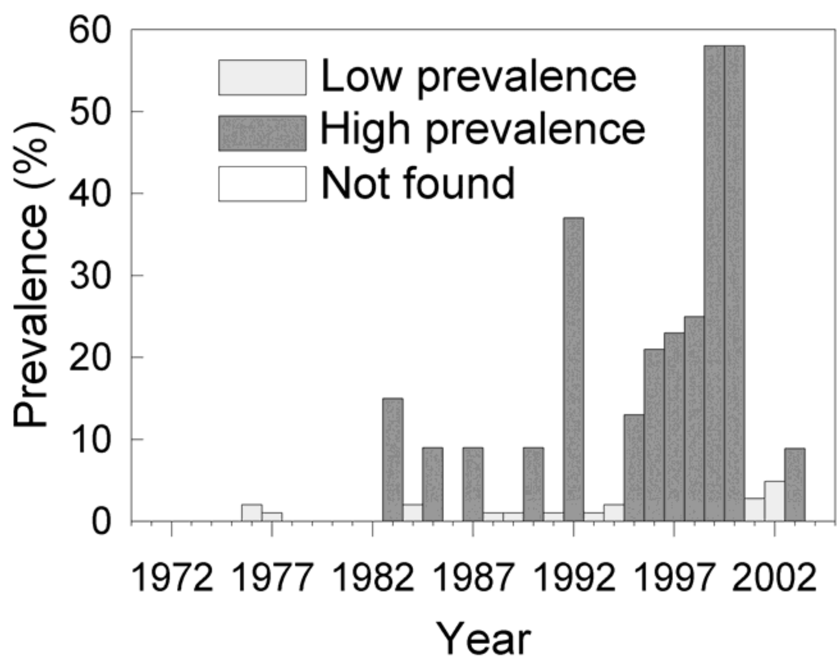

Fig. 1. Prevalence of Stewart's disease of corn in Iowa from 1972 to 1999. Prevalence (at the state level) was defined as number of seed corn fields inspected where Stewart's disease occurred, divided by total number of seed corn fields inspected in Iowa. Low prevalence of Stewart's disease was defined for years in which prevalence was <8%, with high prevalence for years with prevalence >8%. Number of fields inspected was fewer than 100 during the early 1970s, but in most years since then, the number of fields inspected was between 500 and 1,300 per year. Seed corn field sizes inspected ranged from minimum (6.4 ha or less) to 100 or more hectares.

1,000. From this bootstrap procedure, two model fit statistics were examined, Somers' D_{xy} and E_{max} (the maximum absolute error between the predicted and calibrated probabilities).

External validation of each forecasting model was performed with data from the 2000 to 2003 seed corn inspections (1). We predicted the probability of Stewart's disease for each county with air temperature data from the prior winter. A "yes" response for Stewart's disease in a county was recorded if the predicted probability was ≥0.5 (1). Each county was then compared with the corresponding actual presence (1) or absence (0) of Stewart's disease based on the IDALS seed corn inspection in that county. The following measures were used to compare the three models: (i) overall prediction accuracy (proportion of correct yes and no classifications of Stewart's disease in a county), (ii) sensitivity (proportion of correctly classified cases of Stewart's disease prevalence in a county), (iii) specificity (proportion of correctly classified cases of no Stewart's disease prevalence in a county), and (iv) the proportion of false positive and false negative predictions of Stewart's disease based on the differences between predicted and actual occurrences (1,9,24).

RESULTS

Model development. All three empirical models (Stevens Model, Stevens-Boewe Model, Iowa State Model) differed in their ability to accurately predict Stewart's disease, which we had hypothesized (Table 3). The Iowa State Model had the highest *c* value (0.720), indicating an increased likelihood of accurately predicting Stewart's disease in a given county. The Stevens Model had a *c* value (0.530) that approximated random predictions, whereas the Stevens-Boewe Model was intermediate (0.628). One problem with fitting the Stevens Model and the Stevens-Boewe Model was that neither model had county-years in the highest disease risk category (3 for the Stevens Model and 5 for the Stevens-Boewe Model). Therefore, no estimate of either coefficient was possible.

For all three models, the odds of Stewart's disease occurring within a county rose with increased air temperature, meaning the models predicted that the probability of Stewart's disease was >0.5 (Table 3). Based on these regression coefficients, Stewart's disease was more likely to occur if either 2 or 3 months were greater than –4.4°C using the Iowa State Model, or if the Stevens or Stevens-Boewe models gave predictions in the light risk category or higher.

Internal bootstrap model validation. Both the Iowa State Model and the Stevens-Boewe Model had maximum absolute errors (E_{max}) between predicted and calibrated probabilities of 1% or less, indicating that these models were not overfitting the observed prevalence data (Table 4). Therefore, based on E_{max}, both models may be applicable to predicting the county level prevalence of Stewart's disease. The Stevens Model was found not to perform adequately, as a high E_{max} was observed (~10%).

External model validation. Of 154 county-years of seed corn inspection data from 2000 to 2003, Stewart's disease was found in 69 (44.8%) counties. Overall, each model predicted the risk or nonrisk of Stewart's disease comparably (Table 5), as the proportion of correct predictions ranged from 0.621 (both Stevens Model and Stevens-Boewe Model) to 0.656 (Iowa State Model). However, large differences among the models were detected for sensitivity and specificity. Sensitivity ranged from 0.176 (Stevens Model) to 0.667 (Iowa State Model) (Table 5). Specificity ranged from 0.647 (Iowa State Model) to 0.976 (Stevens Model) (Table 5). The Stevens Model had the largest false negative prediction (failure to predict the prevalence of Stewart's disease), as 82.4% of the occurrences of Stewart's disease were not predicted, whereas the Iowa State Model was most accurate, with 33.3% false negative predictions. The Stevens-Boewe Model was intermediate, with 57.4% false negative predictions. Conversely, the Iowa State Model had the largest false positive prediction (failure to predict that Stewart's disease would not occur), as 35.3% of the nonoccurrences of Stewart's disease were not predicted, while the Stevens Model (2.4%) and Stevens-Boewe Model (22.3%) had lower false positive predictions.

Table 3. Summary of binary logistic regression for each of three empirical Stewart's disease forecasting models that were fit using weighted maximum likelihood estimation, where the weight was the number of fields inspected in a given county

Stevens Model[a]		Stevens-Boewe Model		Iowa State Model	
Parameter	Estimate (SE)	Parameter	Estimate (SE)	Parameter	Estimate (SE)
Intercept	–0.5765 (0.0164)	Intercept	–0.8502 (0.0188)	Intercept	–1.7840 (0.0519)
Stevens = light to severe[b]	1.0531 (0.0673)	Stevens-Boewe = light	1.6185 (0.0564)	Iowa State = low	0.6361 (0.0592)
		Stevens-Boewe = moderate	1.4263 (0.0683)	Iowa State = moderate	2.2508 (0.0590)
		Stevens-Boewe = severe	1.3268 (0.0680)	Iowa State = high	1.9369 (0.0687)
Model LR[c]	253.4 (1 df)		1,502.4 (3 df)		2,815.0 (3 df)
P	<0.0001		<0.0001		<0.0001
c[d]	0.530		0.628		0.720
D_{xy}[e]	0.060		0.256		0.441

[a] For these forecasting models, models would be interpreted as follows (using the Iowa State method for a "low" risk as an example):

1. If Iowa State Model = 1(low): $P(Y = Stewart's) = \exp(-1.7840 + 0.6361)/[1 + \exp(-1.7840 + 0.6361)] = 0.241$.

[b] No observations of the Stevens = destructive (category = 3), or Stevens-Boewe = severe (category = 5) were observed in the model development dataset.

[c] Model likelihood ratio.

[d] c measures the probability of concordance.

[e] Somers' D_{xy} rank correlation index ($D_{xy} = 2(c - 0.5)$).

Table 4. Fit statistics from internal bootstrap validation of Stewart's disease prevalence data obtained between 1972 and 1999

	Somers' D_{xy} rank correlation					
Model	Original	Training[a]	Testing[b]	Optimism[c]	Corrected[d]	E_{max}[e]
Stevens	0.073	0.073	0.073	0.000	0.074	0.099
Stevens-Boewe	0.259	0.265	0.262	0.003	0.255	0.007
Iowa State	0.411	0.428	0.417	0.011	0.401	0.010

[a] Based on performance of each logistic regression model using the bootstrap samples.

[b] Model accuracy from using the training sample on the original data sample.

[c] A measure of model overfitting and the difference between the training and testing values.

[d] Corrected index is obtained from correcting the original model by subtraction of the optimism from overfitting of the original model.

[e] Maximum absolute error in between predicted and calibrated probabilities.

DISCUSSION

Using the IDALS seed corn inspection database, when coupled with Stewart's disease predictions, enabled us to critically examine the accuracy of three Stewart's disease forecasting models at the county level in Iowa. Although all three Stewart's disease forecasting models rely on air temperature to predict the likelihood of corn flea beetle survival, thereby predicting the potential amount of initial inoculum for the season, the Iowa State Model improved predicting the risk of Stewart's disease prevalence at the county level in Iowa over the Stevens and Stevens-Boewe models.

While overall prediction (62 to 66% prediction accuracy) was similar for the three models, the combination of internal and external validation provided additional information to evaluate the performance of each model. The Stevens and Stevens-Boewe models were both overly risky in predicting Stewart's disease in Iowa, in that they both often failed to predict a risk for Stewart's disease when it occurred in a county. The Stevens Model system predicted a nonabsence risk of Stewart's disease only 6% of the time (gross underprediction), whereas the Stevens-Boewe predicted a nonabsence risk 21% of the time (also greatly underpredicted). Given the number of county-years of Stewart's disease prevalence and weather data used for comparison, it is highly doubtful that the Stevens or Stevens-Boewe models will accurately predict the risk of Stewart's disease occurrence in a county in Iowa. This is because these three models rely on different temperature thresholds, as well as different effects (prevalence versus severity). Furthermore, based on the threshold temperature of 24.0°F (–4.4°C) for the Iowa State Model, our results suggest that the corn flea beetles survive at temperatures lower than either the Stevens or Stevens-Boewe models would predict. For instance, upon examining mean monthly air temperatures during the period 1971 to 2000 within the nine Iowa climate districts, not a single climate district was classified as having a risk of Stewart's disease using either the Stevens or Stevens-Boewe models, even though there was a series of years (1983, 1992, 1995 to 2000) during which prevalence of Stewart's disease was high (Fig. 1).

Relying solely on the Stevens Model or the Stevens-Boewe Model to predict the prevalence of Stewart's disease would have an adverse effect on disease management strategies meant to reduce the risk of Stewart's disease, as predictions from these two models would suggest a minimal yearly risk (overly risky). Although the Stevens and Stevens-Boewe models were originally developed to predict the severity of Stewart's disease epidemics in sweet corn, these models had also been used to predict the risk of Stewart's disease occurrence (i.e., prevalence) in seed corn fields in Iowa (16,17). These models had been applied despite the lack of clear validation that they would be effective in seed corn fields, where interest is in determining if Stewart's disease will occur. Therefore, our results substantiate that the Stevens and Stevens-Boewe models lack sufficient accuracy to predict the prevalence of Stewart's disease in Iowa.

The Iowa State Model greatly reduced the percentage of false negative predictions (33%) compared with the Stevens and Stevens-Boewe models. While this was a significant improvement, additional research is necessary to elucidate the influence of other factors (biological, environmental, the timeframe when inspections are performed) that might further improve model accuracy, especially given that forecasting for Stewart's disease occurs prior to planting and factors during the growing season may potentially influence the occurrence of Stewart's disease in a county. Nutter and Esker (18) suggested that examination of other environmental variables, including snowfall frequency and duration, snow cover duration, soil temperature, and knowledge of Stewart's disease occurrence the preceding season, may significantly improve the accuracy, specificity, and sensitivity of disease forecasts. For example, based on exploratory analyses, it appeared that a mean monthly soil temperature ≥30°F (–1.1°C) was found to favor corn flea beetle survival in years where Stewart's disease prevalence was high (*data not shown*) (18). Furthermore, the preceding season's occurrence of Stewart's disease may be particularly important because this risk factor provides an indirect indication of a potential local source of inoculum (*P. stewartii*–infested corn flea beetles).

Wrongly predicting the actual risk or nonrisk of Stewart's disease in Iowa also has severe economic consequences. For example, if we assume a single 1-ha field of seed corn was inspected per county, we can estimate an economic cost due to both false positive and false negative predictions that is based on either the unnecessary application of a seed and foliar insecticide (false positive) or the inability to export seed corn in relation to actual production costs, plus product development and sales (overhead) costs (false negative) (25). The cost of an insecticide seed treatment, plus one foliar application of insecticide, is approximately $28/ha. Conversely, the economic loss due to the inability to export harvested seed corn is estimated to be approximately $52.50 (based on expected loss for an 80,000 kernel bag of seed [$60], standardized to a planting density of 70,000 kernels per ha) (6,13). Economically, the Iowa State Model would have had the lowest negative impact, as its false predictions would cost $2,220. Both the Stevens and Stevens-Boewe models would have higher negative economic consequences ($2,996 for the Stevens Model and $2,580 for the Stevens-Boewe Model), and the difference between the Stevens and Stevens-Boewe models is due to the Stevens Model having more false negative predictions. Further research is necessary to incorporate economic calculations into Stewart's disease forecasting in order to optimize the probability threshold for disease forecasts to better balance the sensitivity and specificity of forecasting this disease.

Table 5. External validation for the Stevens, Stevens-Boewe, and Iowa State models regarding their ability to predict the prevalence of Stewart's disease in Iowa counties between 2000 and 2003

Validation criteria	Stevens	Stevens-Boewe	Iowa State
Correct prediction[a]	95/153 (0.621)	95/153 (0.621)	101/154 (0.656)
Sensitivity[b]	12/68 (0.176)	29/68 (0.426)	46/69 (0.667)
Specificity[c]	83/85 (0.976)	66/85 (0.777)	55/85 (0.647)
False positive[d]	2/85 (0.024)	19/85 (0.223)	30/85 (0.353)
False negative[e]	56/68 (0.824)	39/68 (0.574)	23/69 (0.333)

[a] Implies the proper classification of 1's (Stewart's disease) and 0's (no Stewart's disease) based on 153 independent samples between 2000 and 2003.

[b] Correct classification of 1's (prevalence of Stewart's disease).

[c] Correct classification of 0's (no Stewart's disease).

[d] Proportion of falsely predicting the prevalence of Stewart's disease when Stewart's disease did not occur.

[e] Proportion of falsely predicting that Stewart's disease would not occur when Stewart's disease in fact did occur.

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LITERATURE CITED

1. Agresti, A. 2002. Categorical Data Analysis, 2nd ed. John Wiley & Sons, Hoboken, NJ.
2. Boewe, G. H. 1949. Late season incidence of Stewart's disease on sweet corn and winter temperatures in Illinois, 1944-1948. Plant Dis. Rep. 33:192-194.

3. Campbell, C. L., and Madden, L. V. 1990. Introduction to Plant Disease Epidemiology. John Wiley & Sons, New York.
4. Dill, J. F. 1979. Biology and management of the corn flea beetle, *Chaetocnema pulicaria* Melshheimer, relative to the incidence of Stewart's disease in corn. Ph.D. thesis. Purdue University, West Lafayette, IN.
5. Efron, B., and Tibshirani, R. J. 1993. An Introduction to the Bootstrap. Chapman & Hall/CRC, Boca Raton, FL.
6. Esker, P. D. 2005. Epidemiology and management of Stewart's disease of corn in Iowa: Disease forecasting and avoidance. Ph.D. thesis. Iowa State University, Ames.
7. Esker, P. D., Obrycki, J., and Nutter, F. W., Jr. 2002. Temporal distribution of *Chaetocnema pulicaria* (Coleoptera: Chrysomelidae) populations in Iowa. J. Econ. Entomol. 95:739-747.
8. Freeman, N. D., and Pataky, J. K. 2001. Levels of Stewart's wilt resistance necessary to prevent reductions in yield of sweet corn hybrids. Plant Dis. 85:1278-1284.
9. Harrell, F. E., Jr. 2001. Regression Modeling Strategies: With Applications to Linear Models, Logistic Regression, and Survival Analysis. Springer-Verlag, New York.
10. Krause, R. A., and Massie, L. B. 1975. Predictive systems: Modern approaches to disease control. Annu. Rev. Phytopathol. 13:31-47.
11. Kuhar, T. P., Stivers-Young, L. J., Hoffman, M. P., and Taylor, A. G. 2002. Control of corn flea beetle and Stewart's wilt in sweet corn with imidacloprid and thiamethoxam seed treatments. Crop Prot. 21:25-31.
12. McGee, D. C. 1995. Epidemiological approach to disease management through seed technology. Annu. Rev. Phytopathol. 33:445-466.
13. Menelas, B. 2003. Epidemiology and management of *Pantoea stewartii* in the Stewart's disease of corn/corn flea beetle pathosystem. M.S. thesis. Iowa State University, Ames.
14. Mila, A. L., Carriquiry, A. L., and Yang, X. B. 2004. Logistic regression modeling of prevalence of soybean Sclerotinia stem rot in the north-central region of the United States. Phytopathology 94:102-110.
15. Munkvold, G. P., McGee, D. C., and Iles, A. 1996. Effects of imidacloprid seed treatment of corn on foliar feeding and *Erwinia stewartii* transmission by the corn flea beetle. Plant Dis. 80:747-749.
16. Munkvold, G. P., and Rice, M. 1996. Stewart's disease risk for 1996. Integrated Crop Management, Iowa State University Extension, Ames. Online publication.
17. Munkvold, G. P., and Rice, M. 1997. Stewart's disease risk for 1997. Integrated Crop Management, Iowa State University Extension, Ames. Online publication.
18. Nutter, F. W., Jr., and Esker, P. D. 2005. Evaluation of the Iowa State Model to predict the seasonal risk for Stewart's disease of corn. (Abstr.) Phytopathology 95:S165.
19. Nutter, F. W., Rubsam, R. R., Taylor, S. E., Harri, J. A., and Esker, P. D. 2002. Use of geospatially-referenced disease and weather data to improve site-specific forecasts for Stewart's disease of corn in the U.S. corn belt. Comput. Electron. Agric. 37:7-14.
20. Pataky, J. K. 2003. Stewart's wilt of corn. APSNet Feature Story July-August 2003. American Phytopathological Society, St. Paul, MN. Online publication.
21. Pataky, J. K., Michener, P. M., Freeman, N. D., Weinzierl, R. A., and Teyker, R. H. 2000. Control of Stewart's wilt in sweet corn with seed treatment insecticides. Plant Dis. 84:1104-1108.
22. Pataky, J. K., Michener, P. M., Freeman, N. D., Whalen, J. M., Hawk, J. A., Weldekidan, T., and Teyker, R. H. 2005. Rates of seed treatment insecticides and control of Stewart's wilt in sweet corn. Plant Dis. 89:262-268.
23. Pataky, J. K., Suparyono, Hawk, J. A., Gardiner, M. L., and Pauly, M. H. 1990. Associations between Stewart's wilt ratings and maturity of sweet corn hybrids. Plant Dis. 74:792-796.
24. Paul, P. A., and Munkvold, G. P. 2004. A model-based approach to preplanting risk assessment for gray leaf spot of maize. Phytopathology 94:1350-1357.
25. Pepe, M. S. 2003. The Statistical Evaluation of Medical Tests for Classification and Prediction. Oxford University Press, Oxford.
26. Stevens, N. E. 1934. Stewart's disease in relation to winter temperatures. Plant Dis. Rep. 18:141-149.
27. Suparyono and Pataky, J. K. 1989. Influence of host resistance and growth stage at the time of inoculation on Stewart's wilt and Goss's wilt development and sweet corn hybrid yield. Plant Dis. 73:339-345.
28. Young, H. C., Jr., Prescott, J. M., and Saari, E. E. 1978. Role of disease monitoring in preventing epidemics. Annu. Rev. Phytopathol. 16:263-285.
29. Zadoks, J. C., and Schein, R. D. 1979. Epidemiology and Plant Disease Management. Oxford University Press, New York.