INFLUENCE OF WEATHER VARIABLES ON THE FIRST SEASONAL OCCURRENCE OF THE GRAPE BERRY MOTHS *EUPOECILIA AMBIGUELLA* (LEPIDOPTERA: TORTRICIDAE) AND *LOBESIA BOTRANA* (LEPIDOPTERA: TORTRICIDAE) IN A CASE STUDY REGION IN AUSTRIA

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The present case study analyses long term monitoring data (1982 to 2018) of the first occurrence of adult grape berry moth (*Eupoecilia ambiguella* and *Lobesia botrana*) during the growing season on three selected site clusters in Austria with regard to a potential influence of selected indicators related to weather variables. Adult flight was monitored with standard pheromone traps or with the branch cage method. Currently applied degree-day models and a newly developed regression-based combination model were compared for their forecasting performance in this context. On average of all monitoring years the first occurrence of *E.* ambiguella and *L. botrana* was observed 6 to 10 days earlier at the climatically warmest site cluster Vienna/Groß-Enzersdorf compared to the two other site clusters Krems and Langenlois. The existing degree-day models (Freiburg and Neustadt) for *E. ambiguella* and *L. botrana* predicted the first adult occurrence in most of the observation years on average 5 to 13 days too early at all site clusters. However, the model Freiburg predicted the first appearance of *E. ambiguella* at the site cluster Langenlois and of *L. botrana* at the site cluster Vienna/Groß-Enzersdorf also too late in 30 % of the observation years. The analysis of the influence of the single selected weather-related indicators showed that for the first occurrence of the adults for *E. ambiguella* the number of days <11 °C daily mean temperature and for *L. botrana* the mean temperature from January to May were the most determining factors at all three site clusters. The accumulated precipitation and the number of days with precipitation was of little or no importance for the occurrence of both species. Based on this analysis a combined model was created applying multiple regression of all four weather-related indicators from the period January to May. The combined model predicted the first appearance date for both species with mean deviations of only 0.2 to 1.3 days. The present case study has shown that the new combined model improves forecasting performance of the first appearance date for adult *E. ambiguella* and *L. botrana* in the selected regions compared to the existing degree-day models currently in use. With regard to practical use of the developed combined model a further validation and potential improvement with additional data from other sites, for the 2nd generation as well as for other developmental stages of the grape berry moths is planned.
Keywords: monitoring, Lepidoptera, viticulture, degree-day model, regression-based forecasting model

Einfluss von Wettervariablen auf das erste saisonale Auftreten der Traubenwickler-Arten Eupoecilia ambiguella (Lepidoptera: Tortricidae) und Lobesia botrana (Lepidoptera: Tortricidae) in einer Fallstudienregion in Österreich. Die vorliegende Fallstudie analysiert Langzeit-Monitoring-Daten (1982 bis 2018) des ersten Auftretens von adulten Traubenwicklern (*Eupoecilia ambiguella* und *Lobesia botrana)* während der Vegetationsperiode an drei ausgewählten Standortclustern in Österreich im Hinblick auf einen möglichen Einfluss ausgewählter wetterbasierter Indikatoren. Der Flug von Imagines wurde mit Standard-Pheromonfallen oder mit der Käfigmethode überwacht. Dabei wurden zwei aktuell angewandte Temperatursummenmodelle und ein neu entwickeltes Kombinationsmodell hinsichtlich ihrer Prognosegüte verglichen. Im Durchschnitt aller Beobachtungsjahre wurde das erste Auftreten von *E. ambiguella* und *L. botrana* am klimatisch wärmsten Standortcluster Wien/Groß-Enzersdorf 6 bzw. 10 Tage früher als an den beiden anderen Standortclustern Krems und Langenlois beobachtet. Die Temperatursummen-Modelle (Freiburg und Neustadt) für *E. ambiguella* und *L. botrana* prognostizierten das erste Auftreten von Adulten in den meisten Beobachtungsjahren im Durchschnitt aller Standortcluster um 5 bis 13 Tage zu früh. Das Modell Freiburg prognostizierte jedoch das erste Auftreten von *E. ambiguella* am Standortcluster Langenlois und von *L. botrana* am Standortcluster Wien/Groß-Enzersdorf in 30 % der Beobachtungsjahre zu spät. Die Analyse des Einflusses einzelner witterungsbasierter Indikatoren auf das erste Auftreten der Falter zeigte, dass für *E. ambiguella* die Anzahl der Tage <11 °C Tagesmitteltemperatur und für *L. botrana* die mittlere Lufttemperatur von Januar bis Mai an allen drei Standortclustern entscheidend war. Der kumulierte Niederschlag und die Anzahl der Tage mit Niederschlag hatten auf das Auftreten beider Arten kaum oder keinen Einfluss. Basierend auf dieser Analyse wurde ein Kombinationsmodell unter Verwendung einer multivariaten Regression der vier genannten witterungsbasierten Indikatoren aus dem Zeitraum Januar bis Mai erstellt. Das Kombinationsmodell prognostizierte für beide Arten das Datum des Erstauftretens der Adulten mit mittleren Abweichungen von nur 0,2 bis 1,3 Tagen. Die vorliegende Fallstudie hat gezeigt, dass das neue Kombinationsmodell zu einer verbesserten Vorhersagegüte für das erste Auftreten von adulten *E. ambiguella* und *L. botrana* für die getesteten Regionen führt. Im Hinblick auf eine praktische Anwendung des entwickelten Kombinationsmodells ist eine weitere Validierung und Verbesserung mit zusätzlichen Daten von anderen Standorten, für die zweite Generation sowie für andere Entwicklungsstadien des Traubenwicklers geplant.

Schlagwörter: Monitoring, Lepidoptera, Weinbau, Temperatursummen-Modell, regressionsbasiertes Prognosemodell

The grape berry moth species *Eupoecilia ambiguella* and *Lobesia botrana* belong to the most important arthropod pests in viticulture causing economic damage mainly by feeding of the 2nd generation instars on the grape berries (Hoppmann und Holst, 1989; Markheiser et al., 2017). Both species occur under current climate conditions usually with two, but weather dependent also with three generations per year in Austria (Redl et al., 1996). Monitoring of the first occurrence of adults of the first two generations at the start and during the growing season provides important information for appropriate scheduling and optimization of subsequent plant protection measures against this grapevine pest, especially when implemented into pest forecasting models. Climate change is assumed to advance the date of first occurrence of arthropod pests in temperate zones (Bradshaw et al., 2016). Thus, it is of interest to analyse long-term monitoring data in context with weather related indicators for selected sites in Austria. The present case study analyses the potential influence of four weather related indicators on the first occurrence of adult grape berry moths in the growing season at three selected site clusters in Austria, based on long-term pest monitoring data (1982 to 2018) from operational forecasting services in Austria (Polesny et al., 2000; Bauer et al., 2017; Rebschutzdienst, 2018). The study should generate information about the first date and duration of occurrence of adults of both grape berry moth species at the selected site clusters in the context of weather variables. Additionally, different forecasting models – the currently used two degree-day models and a newly developed combination model based on regression of weather related indicators to predict the first occurrence of the grape berry moth adults – were compared for their forecast performance.

MATERIALS AND METHODS

MATERIALS

The monitoring data of the adult flight of both grape moth species used in the present case study were collected at the monitoring site clusters (Table 1) throughout an observation period from 1982 to 2018 with commercially available pheromone traps from different manufacturers and/or the branch cage method as part of warning service activities in Austria (Boller, 1976; Höbaus, 1988; Polesny et al., 2000; Bauer et al., 2017; https://www.warndienst-pflanzengesundheit.at/warndienst/kategorie/weinbau/; https://rebschutzdienst.at/insect-watch). The number of grape moth adults in the pheromone traps was recorded every two to three days under field conditions by different supervisors. For this reason, the periods of these monitoring data do not always correspond with the absolute, actual first day of occurrence or flight start of the adults.
The meteorological data were derived from weather stations in Krems, Langenlois and Groß-Enzersdorf of the Central Institute for Meteorology and Geodynamics (ZAMG) from 1982 to 2018. The meteorological data comprised daily data of the mean, minimum and maximum air temperature (°C), respectively, and precipitation (mm). The sites of the monitoring data used were assigned to the nearest weather station of the Central Institute for Meteorology and Geodynamics (ZAMG) and clustered (Table 1).

METHODS

The monitoring data, particularly the number of grape moth adults per trap, date and site cluster, were used to calculate the temperature sums for the first appearance of adult grape moths according to the Neustadt model (VITIMETEO, 2019a), (sum of daily maximum temperature from March, 1st, until first appearance of adults) and the Freiburg model (VITIMETEO, 2019b), (sum of daily maximum temperature from January, 1st, until first appearance of adults) with a base temperature of 0 °C for both models (https://www.dlr-rheinpfalz.rlp.de/; http://www.agrometeo.de/tw/tw.shtml).
The new combination model was created by using multiple regression on the basis of four weather related indicators (from January to May: daily mean temperature; precipitation sum; number of days <11 °C daily mean temperature; number of days with precipitation). The site clusters Krems and Langenlois were used as calibration sites for the model generation and the site cluster Vienna/Groß-Enzersdorf for the validation.
The general equation for the multiregression model (combination model) is as follows:

Table 1: Survey of monitoring site clusters

Site cluster	Observation sites (communities)	Observation sites with	
		pheromone traps	branch cage
Vienna/Groß-Enzersdorf	Vienna, Klosterneuburg	3	2
Langenlois	Fels/Wagram, Gösing/Wagram, Feuersbrunn. Strass/Strassertal, Hadersdorf, Langenlois, Zöbing, Schönberg am Kamp	7	1
Krems	Krems, Furth bei Göttweig, Unterloiben, Rossatz, Weissenkirchen	4	2

D = Y + B*X1 + C*X2 + D*X3 + E*X4

D = day of occurrence
Parameters:
Y = constant
B = average temperature (Jan-May)
C = precipitation sum (Jan-May)
D = number of days below 11°C daily mean temperature (Jan-May)
E = number of days with precipitation (Jan-May)

Calibrated Formula for *Eupoecilia ambiguella*:
D=50.54+(B*-0.688)+(C*0.002)+(D*0.632)+(E*0.138)
Calibrated Formula for *Lobesia botrana*:
D=115.52+(B*-2.393)+(C*-0.008)+(D*0.159)+(E*0.137)

RESULTS

INFLUENCE OF MONITORING SITE CLUSTERS ON DATE OF FIRST OCCURRENCE OF ADULT GRAPE BERRY MOTHS

The first occurrence of adult *E. ambiguella* was observed at the site cluster Vienna/Groß-Enzersdorf on average 6 days earlier than at the site cluster Langenlois and 7 days earlier than at the site cluster Krems (Fig. 1).

The first occurrence of adult *L. botrana* was observed at the site cluster Vienna/Groß-Enzersdorf on average 7 days earlier than at the site cluster Krems and 10 days earlier than at the site cluster Langenlois (Fig. 2).

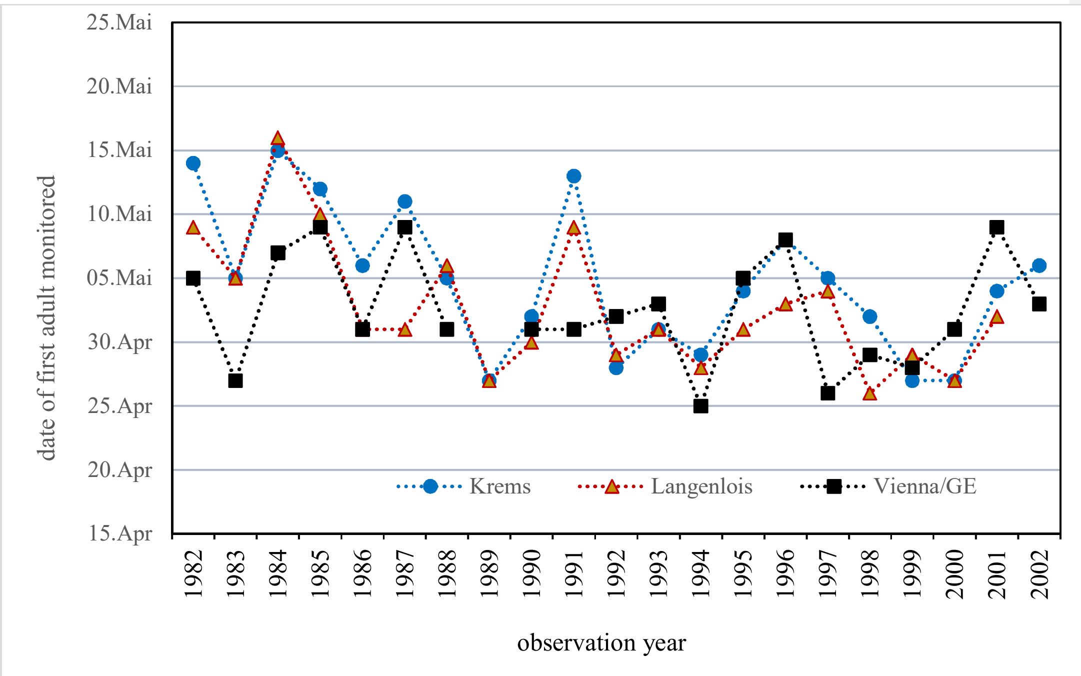

Fig. 1: Date of first occurrence of adult *E. ambiguella* at the three site clusters Krems, Langenlois und Vienna/Groß-Enzersdorf (GE)

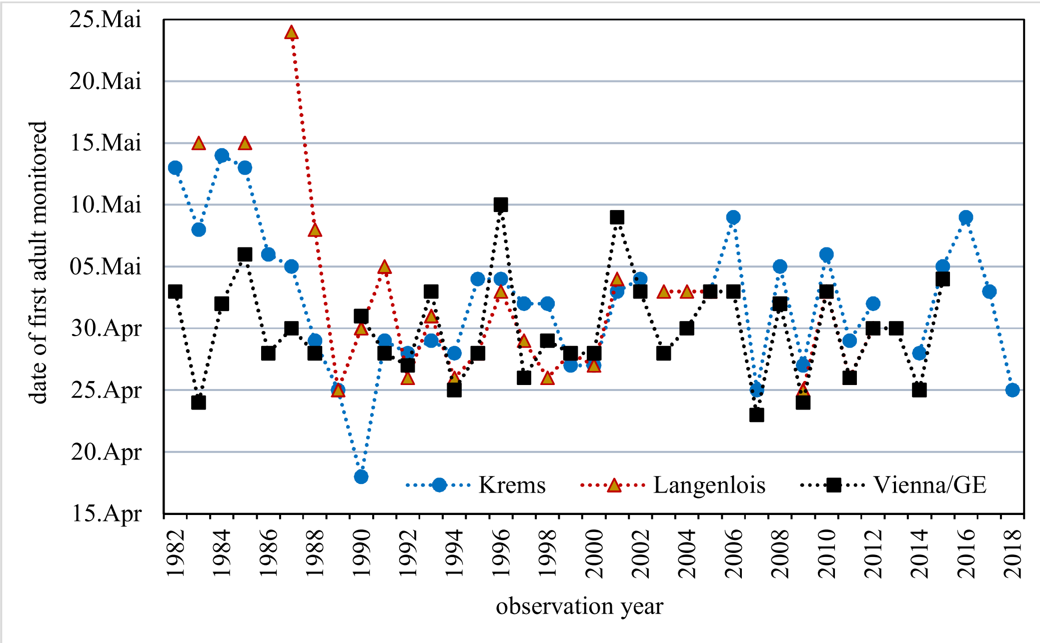

Fig. 2: Date of first occurrence of adult *L. botrana* at the three site clusters Krems, Langenlois und Vienna/ Groß-Enzersdorf (GE)

DATE OF FIRST OCCURRENCE OF ADULT GRAPE BERRY MOTH CALCULATED WITH THE DEGREE-DAY (DD) MODELS COMPARED TO OBSERVED FIRST ADULT OCCURENCE

The calculated degree-days for the first occurrence of the adult grape berry moth at the three site clusters were compared with the two threshold values of temperature sums of the Freiburg model (threshold: 900 dd) and of the Neustadt model, respectively (threshold: 620 dd), for selected observation years. Both models predicted the first occurrence of *E. ambiguella* and *L. botrana* too early for most of the observation years at all site clusters. The Neustadt model predicted the first occurrence of *E. ambiguella* on average 12 days too early at the Krems site cluster and 10 days too early at the Langenlois site cluster. The Freiburg model predicted the first occurrence of *E. ambiguella* on average 13 days too early at the Krems site cluster, but 5 days too late in 30 % of the years at the Langenlois site cluster (Fig. 3).

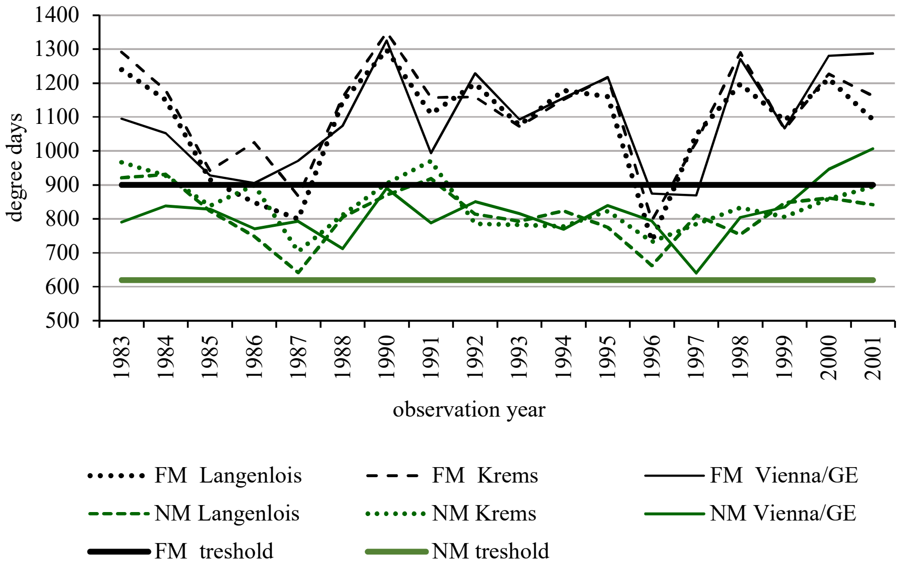

Fig. 3: Actual temperature sums of the observed first occurrence of adult *E. ambiguella* at the three site clusters compared to the thresholds of the temperature sum models (FM: Freistadt model; NM: Neustadt model)

The Freiburg model predicted the first occurrence of *L. botrana* at the Langenlois site cluster on average 10 days and the Neustadt model 9 days too early (Fig. 4). The Neustadt model predicted the first occurrence of *L. botrana* at the site cluster Vienna/Groß-Enzersdorf on average 5 days too early, the Freiburg model in 30 % of the years about 3 days too late (Fig. 4).

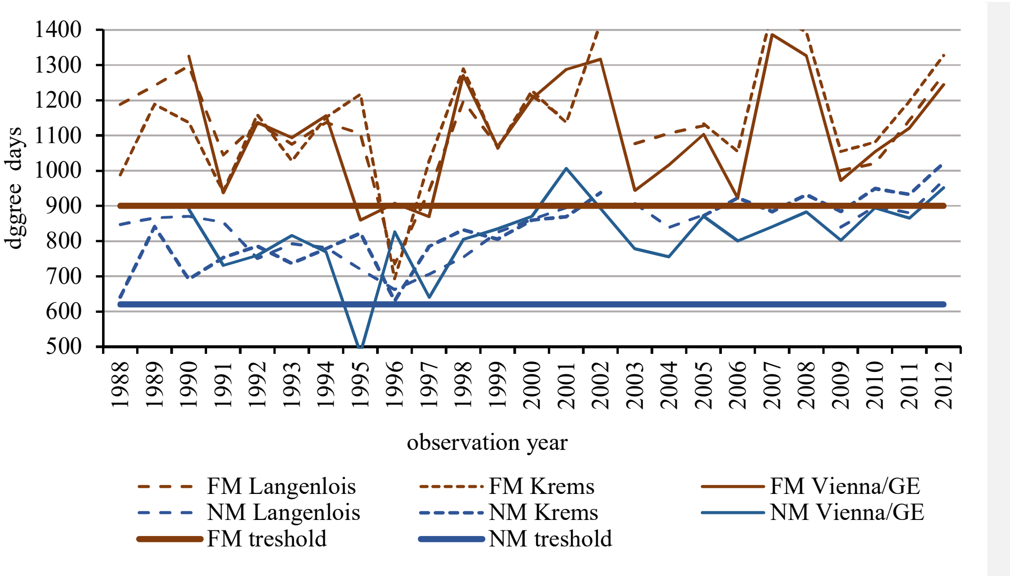

Fig. 4: Actual temperature sums of the observed first occurrence of adult *L. botrana* at the three site clusters compared to the thresholds of the temperature sum models (FM: Freistadt model; NM: Neustadt model)

DURATION OF OCCURRENCE OF 1ST GENERATION OF EUPOECILIA AMBIGUELLA AND LOBESIA BOTRANA AT THE MONITORING SITE CLUSTERS

The observed duration of the flight period of the 1st generation of both grape berry moth species based on the trap catches was similar between the two species at all site clusters and between the site clusters (Figs. 5 and 6).

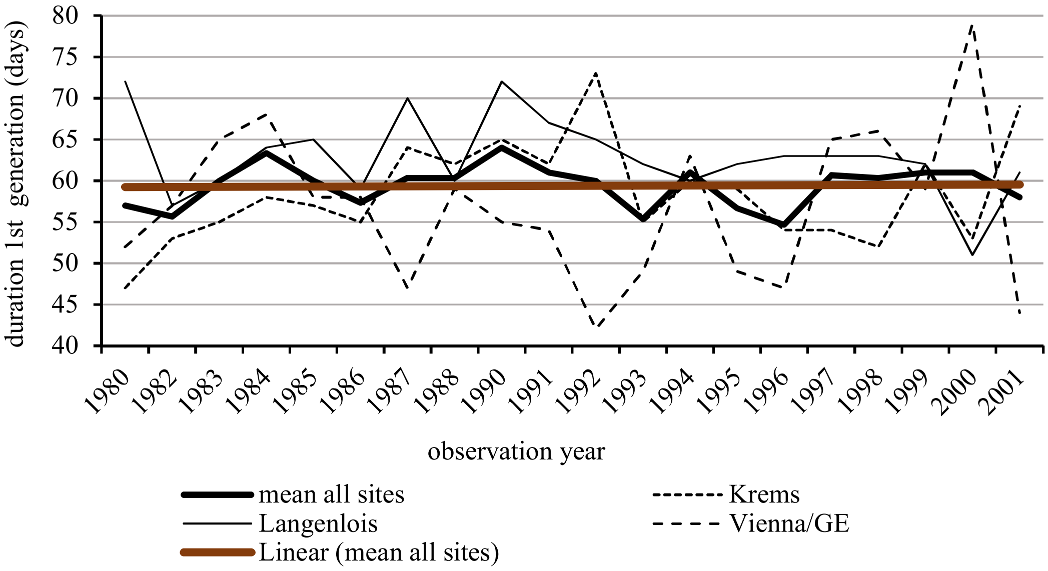

Fig. 5: Mean duration of *Eupoecilia ambiguella* 1st generation flight period at all 3 site clusters over the monitoring years

The mean duration of the 1st *Eupoecilia ambiguella* generation flight period varied from 55 to 64 days during the observation years for the combined monitoring data of all three site clusters.

The range of the mean flight duration of the 1st generation of *Eupoecilia ambiguella* was similar for the three site clusters and varied between 47 to 73 days at the site cluster Krems, 51 to 72 days at the site cluster Langenlois and 47 to 79 days at the site cluster Vienna/Groß-Enzersdorf indicating that there is no difference in the temperature response of *Eupoecilia ambiguella* between the different regions (Fig. 5).

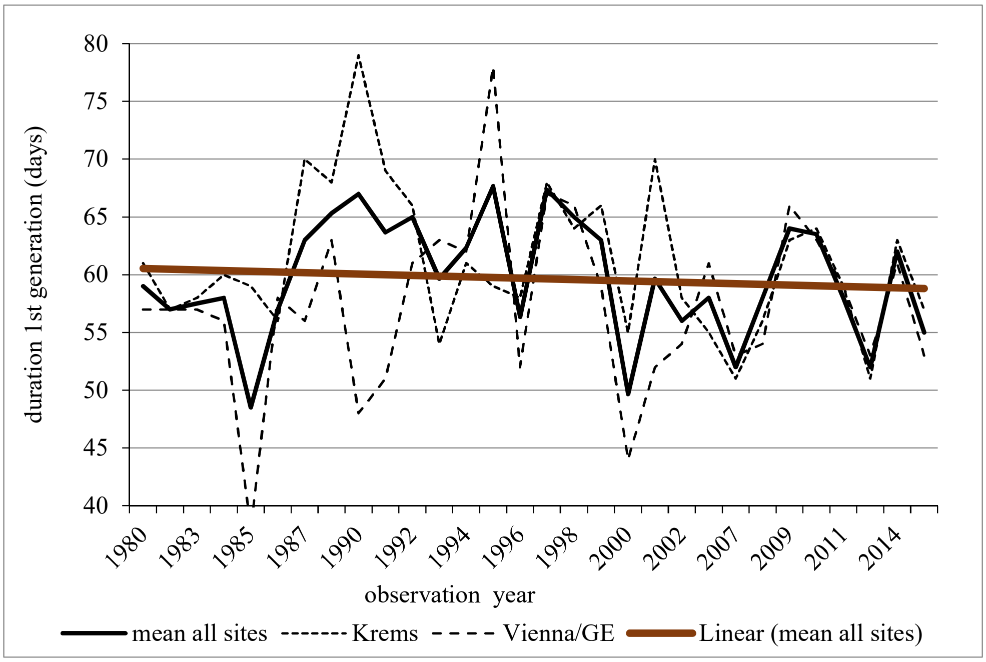

Fig. 6: Mean duration of *Lobesia botrana* 1st generation flight period at 2 site clusters over the monitoring years

The observed mean duration of the flight period of the 1st *Lobesia botrana* generation lasted from 49 to 68 days during the observation years for the combined monitoring data of all three site clusters.

The range of the mean flight duration of the 1st generation of *Lobesia botrana* was similar for the three site clusters and varied between 51 to 79 days at the site cluster Krems, 47 to 75 days at the site cluster Langenlois (not presented) and 38 to 80 days at the site cluster Vienna/Groß-Enzersdorf, indicating that there was no difference in the temperature response of *Lobesia botrana* between the different regions (Fig. 6).

Data from the site cluster Langenlois were not available for all observation years.

INFLUENCE OF WEATHER VARIABLES ON THE DATE OF FIRST OCCURRENCE OF BOTH GRAPE MOTH SPECIES

For both *E. ambiguella* and *L. botrana*, daily mean air temperature had the strongest influence on the time of first occurrence of the adults at all three site clusters. For *E. ambiguella,* the number of days below 11 °C daily mean air temperature (lower temperature threshold for hatching of adults) had the highest coefficient of determination (R^2 of 0.574; 0.624 and 0.361, respectively) for the time of occurrence at the site clusters. For *L. botrana* the daily mean air temperature from January till May played the greatest role for the time of occurrence compared to the other variables. In general, *E. ambiguella* responded more strongly to air temperature than *L. botrana*. The precipitation sum and days with precipitation showed a low coefficient of determination and thus had little influence on the time of occurrence of *E. ambiguella* and *L. botrana* (Table 2).

Table 2: Coefficient of determination (R^2) and its significance (t-Test) of various weather variables from January until May in connection with the first occurrence of *E. ambiguella* and *L. botrana* at the three site clusters. Significance is indicated as ***=<0.0001; **=<0.001; *=<0.01; no asterisk=>0.1.

weather variable	***Eupoecilia ambiguella***	***Lobesia botrana***
	Krems site cluster	
	R^2	**R^2**
Mean air temperature	0.446***	0.241***
Precipitation sum	0.070**	0.016***
Number of days with precipitation	0.043***	0.164***
Days <11 °C mean air temperature	0.574***	0.202***
	Langenlois site cluster	
Mean air temperature	0.336***	0.517***
Precipitation sum	0.021*	0.014***
Number of days with precipitation	0.025***	0.026***
Days <11 °C mean air temperature	0.624***	0.190***
	Vienna/Groß-Enzersdorf site cluster	
Mean air temperature	0.346***	0.192***
Precipitation sum	0.006***	0.002***
Number of days with precipitation	0.055***	0.004***
Days <11 °C mean air temperature	0.361***	0.125***

HOW DO WEATHER VARIABLES AFFECT THE TIME OF OCCURRENCE OF THE TWO TYPES OF PESTS?

COMBINATION MODEL AND THE TEMPERATURE SUM MODELS AT THE KREMS SITE CLUSTER

The dates of the first occurrence of the adult grape berry moths at the Krems site cluster calculated with the combination model (based on multiple regression) correlated relatively well with the actually observed dates of the first occurrence of *E. ambiguella* and *L. botrana* with only a few exceptions.

In contrast, large differences were found between the dates of the first occurrence of adult grape berry moths calculated with the Neustadt and Freiburg models and the observed first occurrence of *E. ambiguella* and *L. botrana.*

At the Krems site cluster, the average deviation between the calculated and the observed date of first occurrence of *E. ambiguella* and *L. botrana* was only 0.2 days for the combined model, but about 13 days for the Neustadt model and 14 days for the Freiburg model, respectively (Fig. 7).

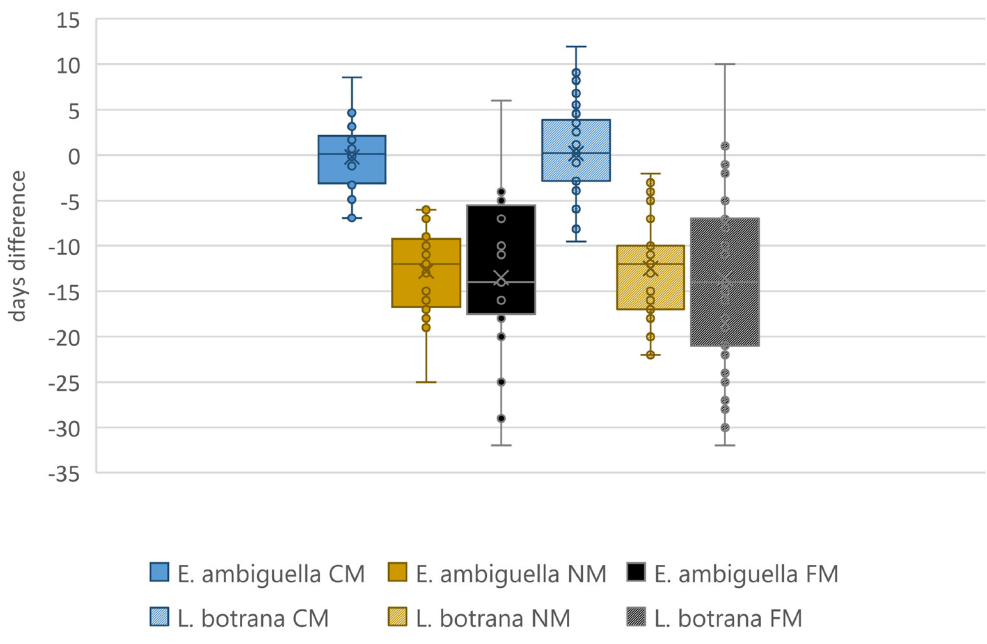

Fig. 7: Deviation of the models (KM: combination model, NM: Neustadt model, FM Freistadt model) from the observed first occurrence in days of *E. ambiguella* and *L. botrana* at the Krems site cluster

The largest deviations between calculated and observed dates of first occurrence for *E. ambiguella* were recorded at the Krems site cluster for the combined model in 1997 (+8.5 days), for the Neustadt model in 1991 (-25 days) and for the Freiburg model in 1990 (-32 days). For *L. botrana* the largest deviation between calculated and observed dates of first occurrence was +11.9 days in 1990 for the combined model, -22 days in 1983 and 2016 for the Neustadt model and -32 days in 2016 for the Freiburg model.

COMBINATION MODEL AND TEMPERATURE SUM MODEL AT THE LANGENLOIS SITE CLUSTER

Also at the Langenlois site cluster the dates of first occurrence of adult *E. ambiguella* and *L. botrana* calculated with the combination model correlated well with the actually observed data.

For the Neustadt and Freiburg models again large differences were found between calculated dates of the first occurrence and the observed first occurrence of *E. ambiguella* and *L. botrana*. Also at this site, the differences between the Neustadt and Freiburg models and the observed first occurrence of *E. ambiguella* and *L. botrana* are bigger than in the combination model.

At the Langenlois site cluster, the average deviation between calculated and observed dates of first occurrence for *E. ambiguella* and *L. botrana* was 0.9 and 0.5 days, respectively, for the combined model, 11 and 12 days, respectively, for the Neustadt model and 10 and 11 days, respectively, for the Freiburg model (Fig. 8).

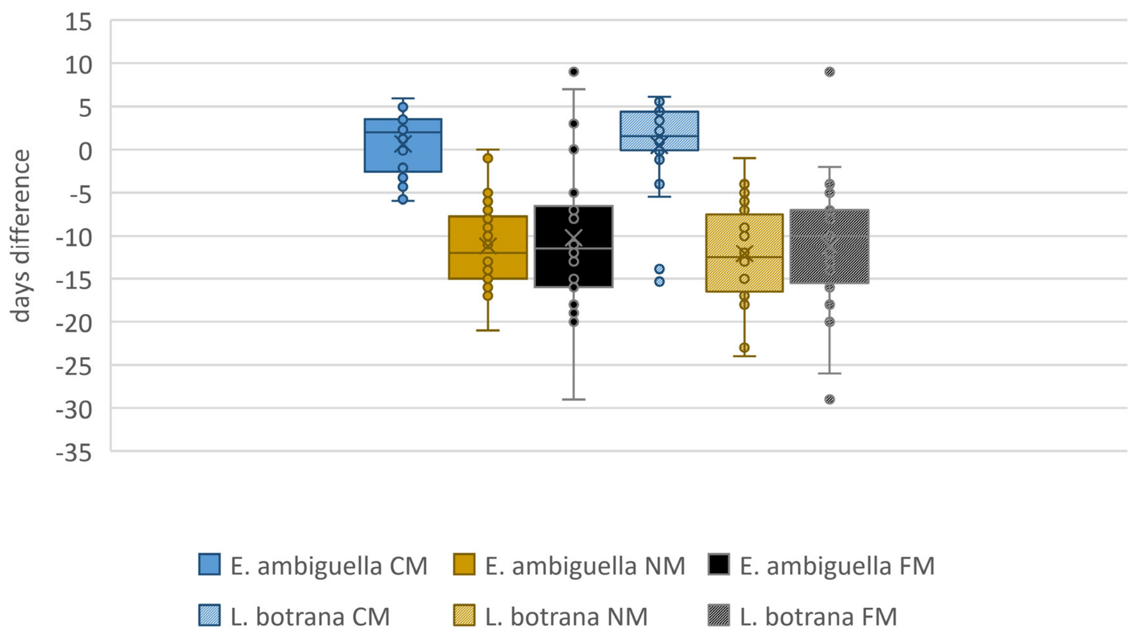

Fig. 8: Deviation of the models (KM: combination model, NM: Neustadt model, FM Freistadt model) from the observed first occurrence in days of *E. ambiguella* and *L. botrana* at the Langenlois site cluster

The largest deviations between calculated and observed dates of first occurrence for *E. ambiguella* were recorded at the Langenlois site cluster for the combined model in in 1983 (-5.9 days) and 1987 (+5.9 days), for the Neustadt model in 1991 (-21 days) and for the Freiburg model in 1990 (-29 days).
For *L. botrana* the largest deviation between calculated and observed dates of first occurrence was -15.3 days in 1983 for the combined model, -24 days in 1983 for the Neustadt model and -29 days in 1990 for the Freiburg model.

COMBINED MODEL VALIDATION RESULTS AT THE SITE CLUSTER VIENNA/GROSS-ENZERSDORF

The combination model predicted relatively well the observed date of the first occurrence of *E. ambiguella* and *L. botrana* with only a few outliers (Figs. 9 and 10).

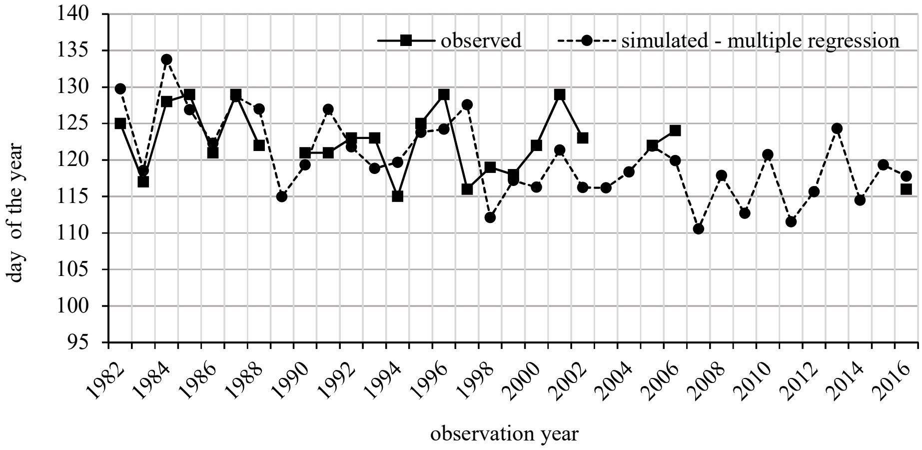

Fig. 9: Combined model for determining the first occurrence of *E. ambiguella* at the Vienna/Groß-Enzersdorf site cluster

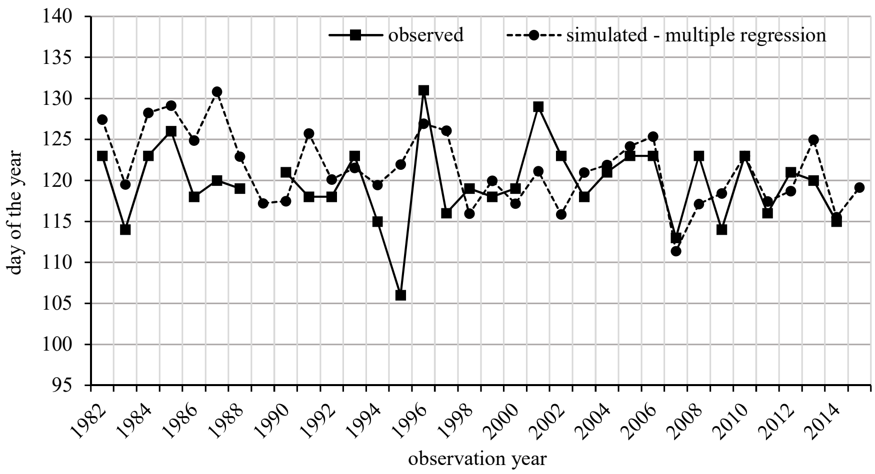

Fig. 10: Combined model for determining the first occurrence of *L. botrana* at the Vienna/Groß-Enzersdorf site cluster

At the Vienna/Groß-Enzersdorf site cluster the average deviation between the observed and calculated dates of first occurrence for *E. ambiguella* and *L. botrana* was 0.2 and 2 days, respectively, for the combined model, 10 days for both species for the Neustadt model, and 11 and 10 days, respectively, for the Freiburg model (Fig. 11). The combined model for E. *ambiguella* showed at the validation sites similar good performing results as at the calibration site clusters. However, for *L. botrana* the mean deviations at the validation sites were slightly higher than at the calibration site clusters.

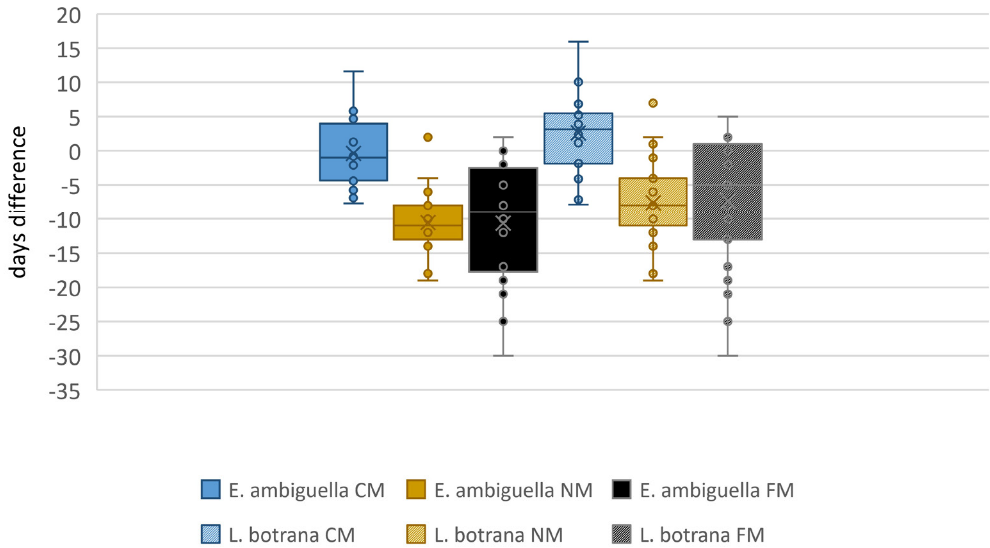

Fig. 11: Deviation of the models for the observed first occurrence of *E. ambiguella* and *L. botrana* at the Vienna/Groß-Enzersdorf site cluster

At the Vienna/Groß-Enzersdorf site cluster, the largest deviation between calculated and observed dates of first adult occurrence for *E. ambiguella* was 11.6 days for the combined model in 1997, 19 days for the Neustadt model in 2001, and 30 days for the Freiburg model in 1990. For *L. botrana*, the largest deviation between calculated and observed dates of first adult occurrence in the combined model was found in the observation year 1987 (+10.8 days), for the Neustadt model in the observation year 2001 (-19 days) and for the Freiburg model in the observation year 1990 (-30 days).

DISCUSSION

The present study shows that the newly developed combination model, which is based on a multiple regression of four selected weather related indicators, makes it possible to predict the first occurrence of adult grape berry moths much more precise than the two temperature sum models currently in use for operational application in Austria. This is due to the consideration of additional weather related indicators by the multiple regression based model, including not only forcing variables (such as the temperature sum in the Neustadt and Freiburg model) but also pest limiting factors. For example, the indicator "number of days with a daily mean temperature <11 °C from January to May" in the combination model is indicating a temperature limitation in addition to the forcing "mean temperature from January to May" parameter. While the individual precipitation-related indicators were according to the coefficient of determination (Table 2) of minor importance for the first occurrence of the adults, the individual temperature-related indicators exerted a major influence on *E. ambiguella* and *L. botrana* development. Of course, this effect may change under different climatic conditions, which should be evaluated in further validation studies, especially considering also local climatic effects for a better explanation of outliers in some cases. The prediction accuracy of the combination model is even more remarkable since the survey data on the first occurrence of grape berry moths were collected under partly changing monitoring conditions with different methods applied over time and sites and by different persons in charge for the observations over a period of almost 40 years. On the one hand, data from catches of pheromone traps from different manufacturers were used, depending on availability. On the other hand, data of adult hatching collected by the cage method were included in the analysis. In addition, the survey data from 15 different sites were merged into three site clusters, as (suitable) weather stations for each site were not available for each individual site to collect the necessary climate data with the required accuracy.

The newly developed regression based combination model to predict the first appearance of adult grape berry moths was successfully tested in a first case study. With regard to the practicable use of the developed model a further validation and potential improvement with additional data from other sites, from the 2nd generation as well as for other developmental stages of the grape berry moths would be recommendable. We further conclude, that past monitoring long-term records of pest occurrence are of inestimable value for such model development and testing studies and should be saved securely for future research.

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