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Predicting the first seasonal occurrence of *Lobesia botrana* and *Eupoecilia ambiguella* in Austria using new multiple linear regression models

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ABSTRACT

Climate change will cause new challenges for sustainable crop production, as increasing temperatures may accelerate the development of thermophilic insect pests and promote their spread and overwintering capacities. Improved or new forecasting models to determine the potential future temporal and spatial shift in the occurrence of the European grapevine moth, *Lobesia botrana* (Denis and Schiffermüller) and the European grape berry moth, *Eupoecilia ambiguella* (Hübner) (Lepidoptera: Tortricidae) could help to better assess these future risks in Austrian wine-growing regions. Additionally, the timing of monitoring and control measures for both these pest species could be optimised to limit crop damages. In this context, prediction models for *Lobesia botrana* and *Eupoecilia ambiguella* were generated using long-term monitoring data (1980 to 2022) from 60 selected monitoring sites in 4 federal states in Austria, which had been collected using two different monitoring methods. Prediction models for the first seasonal occurrence of the different developmental stages (egg, larvae and adult) of the first and second flight/generation of both of the grape moth species were generated by applying stepwise multiple linear regression (MLR) analysis. The validation results showed high prediction accuracy for all six newly generated MLR models for *L. botrana* and for two out of six newly generated MLR models for *E. ambiguella* ($R^2 > 0.6$; RMSE < 4.0; | BIAS | < 2.5). Depending on the developmental stage and generation of *L. botrana,* the validation results displayed an average prediction range of 0.89 days too early to 0.95 days too late. For *E. ambiguella* the predictions were on average 2.85 days too early to 0.20 days too late. To further improve model prediction accuracy, additional datasets should be included in the analysis, especially those from years in which extreme weather events occurred.

KEYWORDS: *Lobesia botrana*, *Eupoecilia ambiguella*, seasonal occurrence, prediction models, multiple linear regression, climate change

INTRODUCTION

Both the European grapevine moth, *Lobesia botrana* (Denis and Schiffermüller) and the European grape berry moth, *Eupoecilia ambiguella* (Hübner) (Lepidoptera: Tortricidae) are considered to be the most impactful Lepidoptera pest of grapevines in Europe (Bovey, 1966; Bournier, 1976; Deseö *et al.*, 1981). The second-generation larvae of both species can cause feeding damage mainly to the berries, leading to subsequent harmful secondary fungal infections (Hoppmann & Holst, 1989; Fermaud & Menn, 1989) and infestation damages of up to 70 % in Austria (Fischer-Colbrie, 1980). In the case of *Lobesia botrana*, up to 90 % infestation damages have been found in Portugal (Carlos *et al.*, 2014). Depending on the geographical region and the prevailing climatic conditions, *L. botrana* can produce up to five generations per year in Europe (Martín-Vertedor *et al.*, 2010; Iltis *et al.*, 2022), while *E. ambiguella* produces only up to three (Bournier, 1976; Schmidt *et al.*, 2003). Recent reviews about the bio-ecology of *L. botrana* and *E. ambiguella* are provided by Benelli *et al.* (2023) and Ricciardi *et al.* (2024), respectively.

It is expected that climate warming in Europe will lead to an earlier first seasonal occurrence of *L. botrana*, shorter developmental cycles and an increase in the number of *L. botrana* generations per year (Martín-Vertedor *et al.*, 2010; Pavan *et al.*, 2013; Reis *et al.*, 2022; Castex *et al.*, 2023). Thus, the predicted future climate scenarios appear to be more favourable for the occurrence of *L. botrana* (Pétremand *et al.*, 2017), as this thermophilic species appears to be better adapted to drier conditions than *E. ambiguella,* and would therefore benefit from climate warming (Bournier, 1976). However, humidity could drop to a level that is insufficient for even *L. botrana* and increased temperatures could reach the upper lethal limit, which would result in an increase in mortality rate of *L. botrana*, and reduce its reproductive success or its voltinism (Svobodová *et al.*, 2014; Moshtaghi Maleki *et al.*, 2016; Gutierrez *et al.*, 2018; Iltis *et al.*, 2020; Castex *et al.*, 2023). Additionally, heatwaves could negatively impact the larval development of *L. botrana* in the future (Iltis *et al.*, 2021) and the phenology of grapevine could also change with increasing temperatures (Santos *et al.,* 2020; Reis *et al.*, 2022). On the one hand, earlier development of the vines could lead to a higher risk of infestation by *L. botrana*, especially shortly before harvest (Castex *et al.*, 2023); on the other hand, the nutritional value of grapevines and their suitability as a host plant for *L. botrana* could decrease with increasing temperatures (Reineke & Thiéry, 2016). Moreover, an increased asynchrony between the phenology of *L. botrana* and that of grapevines could occur (Reis *et al.*, 2022).

In Austria, *L. botrana* was present only in Burgenland in the 1980s, and it spread swiftly until it occurred in a mixed population with *E. ambiguella* (Höbaus, 1988), now usually producing two generations per year. It should be noted, however, that the occurrence of a third generation in Austria has also been described several times since 1988 (Höbaus, 1988; Polesny *et al.*, 2000; Bauer *et al.*, 2017).

For the control of both species in commercial vineyards, mating disruption is predominantly carried out at present (Ioriatti *et al.*, 2011; lkonline, 2023). In this context, regular monitoring is conducted in Austria to determine the best time for intervention measures. Monitoring will face new challenges, as studies suggest that higher temperatures could decrease the efficiency of the pheromone traps (El-Sayed *et al.*, 2021). The timing of monitoring and control measures needs to be adapted to the changes in seasonal pest occurrence and associated changes in population dynamics due to global warming. In order to optimise the timing of monitoring and control measures, precise forecasting models will be required to predict the expected earlier time of the first seasonal occurrence of each developmental stage of each generation of the respective grape moth species.

Several authors have described the use of temperature sum models (*i.e.*, degree-day models) (Boller, 1976; Cravedi & Mazzoni, 1990; Carlos *et al.,* 2018) to predict the first seasonal occurrence of grape moth adults; these are based on data of adult trap catches and air temperature (with specified lower and/or upper temperature threshold) as a single influencing weather parameter. However, temperature sum models have been shown to mismatch the actual first occurrence of *L. botrana* and *E. ambiguella* in Austria (Blümel *et al.*, 2020).

Several other prediction models that also take into account other parameters and differ substantially in terms of type, output, complexity and applicability have been proposed for both grape moth species; for example, distributed delay models (*e.g.*, Di Silvestro *et al.*, 1999), physiologically based demographic models (*e.g.*, Pasquali *et al.*, 2022), age structured Leslie models (*e.g.*, Schmidt *et al.,* 2001), age-structured population models (*e.g.*, Ainseba *et al.*, 2011) and semi-physical models (*e.g.*, Aguirre-Zapata *et al.*, 2023). These models mainly predict the voltinism, spatial distribution and flight peak of both grape moths, as well as other characteristics related to their life. More complete reviews and comparisons of existing predictive models for *L. botrana* are provided by Lessio and Alma (2021) and Castex *et al.* (2020).

Using limited data, multiple linear regression (MLR) models were generated in a previous study (Blümel *et al.*, 2020) in order to predict the seasonal first occurrence of the first flight adults of *L. botrana* and *E. ambiguella.* These models displayed improved prediction accuracy relative to two models based only on temperature sums, which were commonly used in Austria until then. Compared to the latter models, the MLR models incorporated additional weather variables, which had a positive effect on their prediction accuracy (Blümel *et al.*, 2020).

In the present study, new prediction models based on MLR analysis were calibrated and validated using comprehensive long-term monitoring data and weather data from Austria to predict the first seasonal occurrence of the second flight adults, and the egg/larvae stages of the first and second generation of *L. botrana* and *E. ambiguella*. Additionally, the existing MLR models for predicting the first flight adults of *L. botrana*/*E. ambiguella* (Blümel *et al.*, 2020) were adapted and validated.

MATERIALS AND METHODS

1. Monitoring data

For the MLR analysis, monitoring data of the 1st/2nd flight adults and 1st/2nd generation eggs and larvae from both grape moth species were used. The monitoring data derived from four decades-worth (1980-2022) of consecutive observations carried out by the Austrian forecasting services at 60 monitoring sites in different wine-growing regions. These monitoring sites were merged into 14 site clusters according to their proximity to GeoSphere Austria (https://www.geosphere.at) reference weather stations (Table 1).

For the adults of both of the grape moth species, the monitoring data were obtained using one of two methods: i) pheromone trap catches of males using commercially available devices from different manufacturers (for about 10 years, natural rubber dispensers from Pherobank® product No. 50118 for *L. botrana,* comprising (E,Z)-7,9-dodecadienyl acetate and (E,Z)-7,9-dodecadien-1-ol in 0.4 mg/lure; and Pherobank® product No. 50088 for *E. ambiguella* comprising (Z)-9-dodecenyl acetate, dodecyl acetate, hexadecyl acetate and octadecyl acetate in 0.8mg/lure) (Pherobank, 2024), or ii) observations using the branch cage method (Polesny *et al.*, 2000), in which the egg and larval stages were monitored in order to observe the occurrence and development of all generations

TABLE 1. *L. botrana* and *E. ambiguella* monitoring specifications.

No. Site cluster	Monitoring sites	Wine-growing regions	Reference weather station	Coordinates of reference weather stations	Monitoring method + years	
					Pheromone trap	Branch cage
1	St. Anna; St.Stefan ob Stainz; Deutschlandsberg; Kitzeck; Glanz	Vulkanland Steiermark; West-Steiermark; Süd-Steiermark	Wagna-Leibnitz	46°46'03.0"N 15°33'10.0"E	1994 – 2022	2002 – 2022
2	Donnerskirchen; Rust am See	Leithaberg (incl. Rust)	Eisenstadt	47°51'14.0"N 16°32'19.0"E	1980 – 1992	-
3	Gumpoldskirchen	Thermenregion	Gumpolds-kirchen	48°01'15.2"N 16°09'54.4"E	1984 – 2018	2005 – 2022
4	St. Johann; Söchau	Vulkanland Steiermark	Hartberg	47°16'50.0"N 15°58'43.0"E	1994 – 2022	2002 – 2021
5	Vienna; Klosterneuburg	Wien	Stammersdorf	48°18'21.0"N 16°24'20.0"E	1980 – 2018	2002 – 2022
6	Dobermannsdorf	Weinviertel	Hohenau/March	48°36'59.0"N 16°54'16.0"E	1982 – 1994	-
7	Krems; Furth Göttweig; Unterloiben; Rossatz; Weissenkirchen	Kremstal; Wachau	Krems	48°25'06.0"N 15°37'17.0"E	1980 – 2022	2005 – 2020
8	Ahrenberg; Groß Weikersdorf; Ruppersthal	Traisental; Wagram	Stockerau	48°23'49.0"N 16°11'33.0"E	1990 – 2012	-
9	Fels/Wagram; Gösing/ Wagram; Feuersbrunn; Strass/ Strassertal b. L.; Hadersdorf; Langenlois; Zöbing; Schönberg am Kamp	Wagram; Kamptal	Langenlois	48°28'21.0"N 15°41'50.0"E	1980 – 2015	2002 – 2015
10	Deutschkreutz; Neckenmarkt; Horitschon	Mittel-burgenland	Lutzmannsburg	47°27'55.0"N 16°38'44.0"E	1994 – 2001	2002 – 2009
11	Mönchhof	Neusiedlersee	Neusiedl	47°57'03.0"N 16°50'30.0"E	1991 – 2001	-
12	Retz	Weinviertel	Retz	48°45'40.0"N 15°56'30.0"E	1980 – 2022	2002 – 2018
13	Hollabrunn; Obergrabern; Braunsdorf; Hohenwarth-Mühlbach a. Manhartsberg; Pfaffstetten/Maissau; Heldenberg	Weinviertel	Schöngrabern	48°36'12.0"N 16°03'42.0"E	1985 – 2000	2014 – 2018
14	Wolkersdorf; Mistelbach	Weinviertel	Mistelbach	48°34'15.0"N 16°36'36.0"E	1980 – 2017	2002 – 2017

under real-time field conditions (Polesny *et al.*, 2000). Monitoring was carried out for both grape moth species in the different observation years at different intervals (branch cage/pheromone trap control every 1-3 days) and over different observation periods (observing either both flights/generations from mid-April/beginning of May to end of July/beginning of August, or observing only the 2nd flight/generation from end of June/beginning of July to end of July/beginning of August), depending on the practical requirements and possibilities of the warning service operators.

In spring, monitoring usually starts with the observation of the 1st flight adults, which emerge from overwintering pupae (Castex *et al.*, 2018). As the 2nd generation is considered to be the most economically important, monitoring of 2nd flight adults was carried out more frequently (at more sites and in more years) than that of 1st flight adults. Fifty-seven percent and 26 % of the monitoring data of the 1st flight adults for *L. botrana* and *E. ambiguella*, respectively, and 58 % and 53 % of the 2nd flight adults were collected using the branch cage method (Table 2). From the available monitoring data, only the earliest recorded first occurrence per cluster, grape moth species, flight, generation, developmental stage and year of observation was used for the MLR analysis.

TABLE 2. Number of monitoring datasets usable for the MLR analysis.

***L. botrana* – Number of datasets of all site-clusters**							
Monitoring method	1st flight	1st generation		2nd flight	2nd generation		Total sum
	Adults (1980-2022)	Eggs (2002-2019)	Larvae (2002-2019)	Adults (1980-2022)	Eggs (2002-2022)	Larvae (2002-2022)	
Branch cage	44	43	43	85	79	80	374
Pheromone trap	33	-	-	62	-	-	95
Total sum	77	43	43	147	79	80	469
***E. ambiguella* – Number of datasets of all site-clusters**							
Monitoring method	1st flight	1st generation		2nd flight	2nd generation		Total sum
	Adults (1980-2022)	Eggs (2002-2022)	Larvae (2002-2022)	Adults (1980-2022)	Eggs (2002-2021)	Larvae (2002-2021)	
Branch cage	22	22	22	62	51	51	230
Pheromone trap	63	-	-	56	-	-	119
Total	85	22	22	118	51	51	349

2. Meteorological data

The daily meteorological data for the 14 reference weather stations, which were closest to the monitoring site clusters (Table 1) were provided by GeoSphere Austria. The distances between the monitoring sites and respective reference weather stations were as follows: 17 monitoring sites were ≤ 5 km away, 26 sites > 5 to ≤ 10 km, 8 sites > 10 to ≤ 15 km, 4 sites > 15 to ≤ 20 km, and 5 sites > 20 km. Any data gaps (due to, for example, a malfunction of the measuring devices or the relocation of a weather station) were filled with additional data from six alternative weather stations near the monitoring site in question or with SPARTACUS - Spatiotemporal Reanalysis Dataset for Climate in Austria (GeoSphere Austria, 2022) grid datasets. Nine weather parameters obtained daily from the weather stations were processed for the analysis (Table 3). Air temperature was corrected for elevation when the sea level difference between the respective reference weather station and the monitoring site exceeded 100 m (a decrease of 0.6 °C for every 100 m increase of sea level).

3. Existing prediction models

In order to identify existing prediction models for both of the grape moth species, an extensive systematic literature search (ELS) (EFSA, 2010) of the electronic database Ovid was carried out using search terms in the categories taxonomy, development, weather parameters, host plants and prediction models. In order to find models appropriate for testing with monitoring data from Austria, the retrieved publications were classified according to several criteria, such as model type, latitude/region at which the model was developed, the origin of weather data for the calculation of the model, model input parameters (*e.g.*, weather variables and biological parameters), model settings (*e.g.*, calculation period) and model output parameters (*e.g.*, prediction goal of calculation and unit of calculation result).

Four potentially suitable prediction models were selected for model improvement and model generation. The preliminary MLR models for predicting the first seasonal occurrence of 1st flight adults of *L. botrana* and *E. ambiguella* (Blümel *et al.*, 2020) were validated using additional monitoring data. They were then adapted and further improved using additional input parameters (*e.g.*, calculation period, lower and upper temperature thresholds) provided by the two temperature sum models (Gallardo *et al.*, 2009; Carlos *et al.*, 2018) and the physiologically based demographic model (Gutierrez *et al.*, 2012).

TABLE 3. Weather variables considered in the MLR model development.

Weather parameters	Tested weather variables		
	Description	Abbreviation	Unit
Daily maximum air temperature (°C)	Mean daily maximum air temperature	Tmax	°C
	Sum of days with a maximum air temperature greater than the "upper temperature threshold" °C	Tmax > "threshold"	No. days
Daily minimum air temperature (°C)	Mean daily minimum air temperature	Tmin	°C
Daily mean air temperature (°C)	Mean daily mean air temperature	Tmean	°C
	Sum of days with a mean air temperature less than / greater than / equal to a "lower temperature threshold" °C	Tmean < / ≥ "threshold"	No. days
	Sum of daily mean air temperature greater than "adapted lower temperature thresholds" °C	Tbase "threshold"	°C
Daily precipitation (mm)	Sum of daily precipitation	Precipsum	mm
	Sum of days with precipitation	Precip Y/N	No. days
Daily sunshine duration (h)	Sum of daily sunshine duration	Sun-h	h
Daily global radiation (MJ/m²)	Sum of daily global radiation	Rad	MJ/m²
Daily vapour pressure (hPa)	Mean daily vapour pressure	VapP	hPa
Daily wind speed (m/s)	Mean daily wind speed	Wind	m/s
Daily relative humidity (%)	Mean daily relative humidity	RH	%

4. Multiple linear regression analysis

The two pre-existing MLR models for predicting 1st flight adults of *L. botrana*/*E. ambiguella* were adapted with additional monitoring data, and ten new MLR models were generated separately for each of the two grape moth species in order to predict day of year (DOY) for the first seasonal occurrence of 1st generation eggs/larvae, 2nd flight adults and 2nd generation eggs/larvae.

The adapted and new prediction models were developed applying stepwise multiple linear regression (MLR) analysis (IBM® SPSS® Statistics – Version 26) to predict the first seasonal occurrence of each developmental stage of the 1st and 2nd flight/generation for both grape moth species. The general formula for the MLR analysis is shown in equation:

$$y_i = b_0 + b_1 X_{i,1} + b_2 X_{i,2} + \ldots + b_k X_{i,k}$$

where y_i is the dependent variable, b_0 is a statistical constant (y-intercept of the linear regression line), $X_{i,k}$ are independent variables and b_k is the regression coefficient value of the independent variables.

The equations were generated using the DOY of the observed first occurrence of *L. botrana*/*E. ambiguella* adults/eggs/larvae (dependent variable) and processed weather variables (independent variables) (Table 3). The temperature variables were based on the reported lower (Tl) and upper temperature (Tu) thresholds. The adapted threshold values of the variable Tbase "threshold" were determined by performing a sensitivity analysis comprising ± 0.5 °C steps from the reported lower temperature threshold values (Tl: adults = 7 °C, 10 °C and 11 °C; eggs = 8 °C and 14 °C; larvae = 6 °C and 12 °C; Tu: adults, egg and larvae = 30 °C and 32 °C) (Russ, 1966; Gabel, 1981; Touzeau, 1981; Briere & Pracros, 1998; Cravedi & Mazzoni, 1990; Moshtaghi Maleki *et al.*, 2016).

In addition, a number of different monthly (n = 2-11) and weekly (n = 7-36) calculation periods were defined for each developmental stage per flight/generation. For this purpose, the development duration of the adult/egg/larval stage of both flights/generations, the earliest and latest date of the observed first occurrence, as well as the calculation periods implemented in the existing prediction models were taken into account.

A preliminary selection of relevant calculation periods was carried out using the coefficient of determination (R^2). The R^2 was calculated between the different weather variables of different calculation periods and the DOY of observed first seasonal occurrence. The six calculation periods with the highest R^2 were included in the MLR analysis. In the next step the monthly/weekly sums (Tmax > "threshold", Tmean < / ≥ "threshold", Tbase "threshold", Precipsum, Precip Y/N, Sun-h, Rad) and mean values (Tmax, Tmin, Tmean, VapP, Wind, RH) were calculated for each weather variable examined and then once again summed/averaged for the determined calculation periods. All available datasets from the branch cage method were usable and were included in the model calibration and validation. Monitoring data from pheromone trap catches were used for the subsequent model calculations, when

1) a 0-catch observation took place before the initial first occurrence,
2) the transition from 1st to 2nd flight was clearly recognisable (*e.g.*, no adult catches for at least a week around the 3rd quartile in June), and
3) catches were continuously recorded during the complete observation period.

The generation of the final MLR models (n = 12) consisted of i) a calibration comprising the utilisation and adjustment of available input data to ensure that the model output corresponded as much as possible to the observed data, and ii) a validation in which the calibrated MLR model was tested using statistical indicators and additional datasets that had not already been included in the calibration. Individual model equations were calibrated and gradually optimised for the different flights/generations and development stages of each of the two grape moth species. Initially, the monitoring data of the cluster with the most usable datasets and the corresponding processed weather data were used for the model calibration. Subsequently, different calculation periods were tested to optimise the calibrated model equations and, in order to cover regional and annual differences in the generated model as comprehensively as possible, datasets from other clusters were gradually included in the calibration.

The prediction quality of the generated MLR models was classified as high for both flights/generations, with a maximum deviation between the observed and calculated first occurrence of adults of ± 2 days and of ± 4 days for the egg and larvae stages. The deviation ranges took into account the monitoring intervals, the application times of the control measures, the developmental biology (*e.g.*, earlier appearance of male than female moths = protandry), development duration of the individual stages (*e.g.*, Gabel, 1981), as well as the differences in development duration due to different grapevine varieties (Thiéry *et al.*, 2014).

All the datasets from 2022 and at least five unused, independent datasets from previous years per cluster from the model calibration were used to validate the generated model equations. When necessary, the datasets of a cluster were divided between validation and calibration in order to achieve the required amount of data for the final model validation. The calibrated models were validated using the coefficient of determination (R^2), the standard deviation (SD), the root-mean-square error (RMSE) and the mean bias (BIAS).

RESULTS

The analysis of the long-term monitoring data during the 1980-2022 observation period showed a tendency for an earlier first seasonal occurrence of the different developmental stages of both flights/generations of *L. botrana* and *E. ambiguella* at the monitoring sites. Regarding the first seasonal occurrence of *L. botrana*, the adults of the 1st and 2nd flights were 5 and 8 days earlier, respectively, the 1st and 2nd generation eggs 6 and 7 days earlier, respectively and the larvae 7 days earlier (Figures 1 a-b). For the first seasonal occurrence *of E. ambiguella,* the adults of the 1st and 2nd flights were 16 and 9 days earlier, respectively, the 1st and 2nd generation eggs 8 and 2 days earlier, respectively, and the larvae 13 and 2 days earlier, respectively (Figures 1 c-d).

1. Adapted and newly generated MLR models

For each flight/generation and developmental stage of *L. botrana*/*E. ambiguella* separate MLR models were generated. The initially generated equations were continuously improved until models with low deviations between predicted and observed first occurrence in the calibration and validation dataset were achieved. In addition, the generated equations had to achieve at least statistical indicator values with a satisfactory prediction accuracy (very high prediction accuracy: $R^2 > 0.7$, RMSE < 3.0, | BIAS | < 1.0; high prediction accuracy: $R^2 > 0.6$, RMSE < 4.0, | BIAS | < 2.5; satisfactory prediction accuracy: $R^2 > 0.5$, RMSE < 4.5, | BIAS | < 3.0) (Table S1).

The two adapted and the ten newly generated MLR models for *L. botrana*/*E. ambiguella* applied different calculation periods depending on the flight/generation and developmental stage. For the 1st and 2nd flight/generation adults/eggs/larvae of the two grape moth species, different site clusters provided data for the calibration and validation of the generated MLR models (Table S2).

The adapted MLR models for predicting the first seasonal occurrence of 1st flight adults, together with newly generated MLR models for the 2nd flight adults and the remaining developmental stages of 1st and 2nd generation, are described in detail for each grape moth species in the following sections.

1.1 *Lobesia botrana*

For the prediction of the first seasonal occurrence of the adult/egg/larvae stage of 1st and 2nd flight/generation of *L. botrana,* the stepwise multiple linear regression analysis resulted in models that included individual input variables for each developmental stage per flight/generation (Table 4). Almost all the independent variables (= weather variables) were statistically significant ($P < 0.05$) predictors of the dependent variable (= DOY of first seasonal occurrence of *L. botrana* 1st/2nd flight/generation adults/eggs/larvae) (Table 4). Only the input variables "sum of daily global radiation" ($P = 0.310$) of *L. botrana* 1st generation eggs, the "sum of days with precipitation" ($P = 0.223$) and "sum of daily global radiation" ($P = 0.961$) of 1st generation larvae and the "mean daily wind speed" ($P = 0.070$) of 2nd generation larvae displayed no significant effect on the respective DOY of the first seasonal occurrence. The variance inflation factor (VIF) displayed low linear connection between the input variables of each generated MLR model (Table 4). A high linear connection or multicollinearity between the input weather variables would have occurred, if the VIF had exceeded a value of 4 (O'Brien, 2007).

The final MLR equations and their applied monthly or weekly calculation periods for predicting the first seasonal occurrence of *L. botrana* 1st/2nd flight/generation adults/eggs/larvae are presented in Table 5.

The prediction accuracies of the six validated *L. botrana* MLR models, based on the evaluation of the statistical indicators described above, were very high for 1st flight adults, 1st generation larvae and 2nd generation larvae, and high for

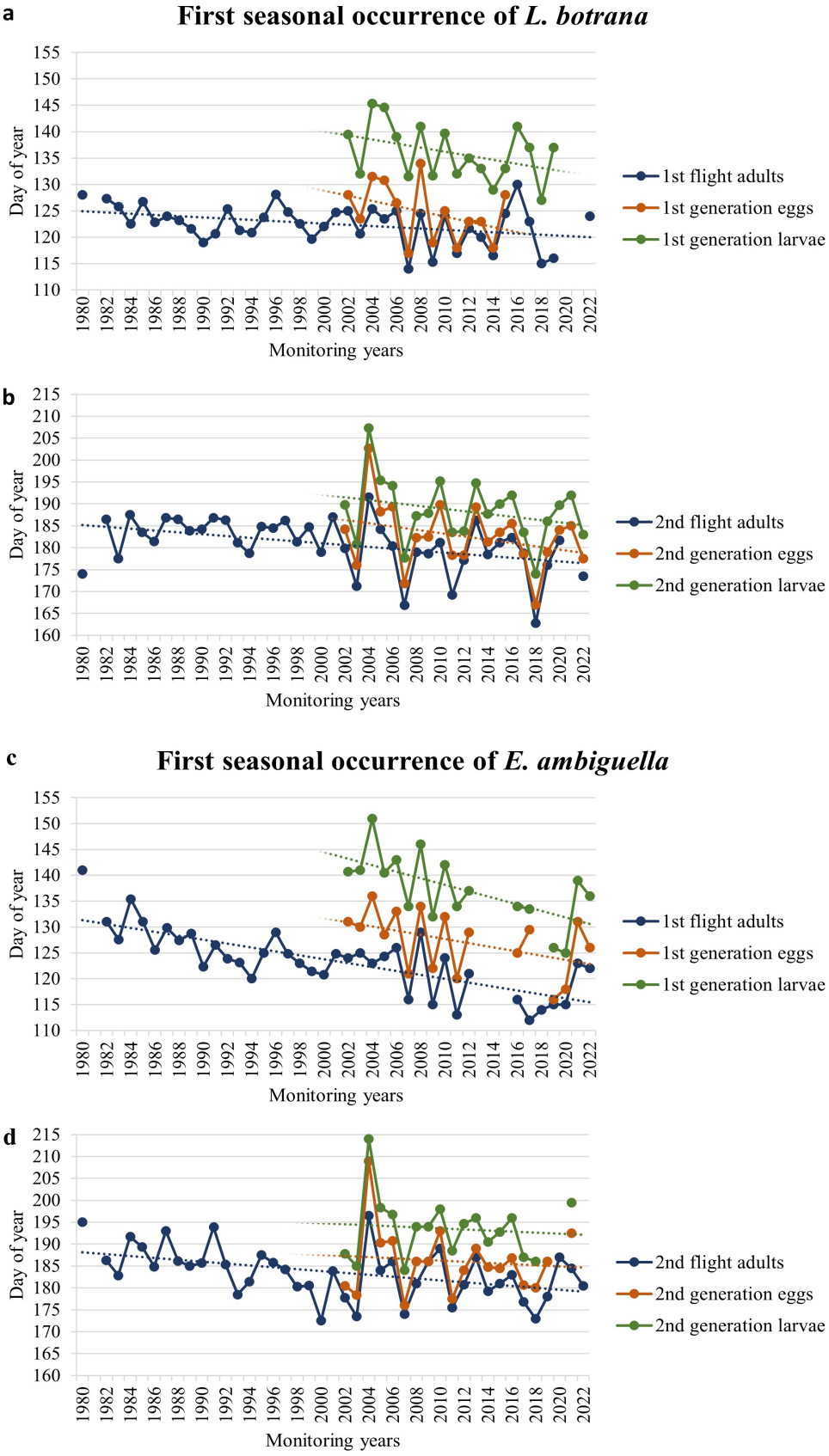


FIGURE 1. Temporal shift of the observed first seasonal occurrence of the 1st (a) and 2nd (b) flight/generation of *L. botrana* and the 1st (c) and 2nd (d) flight/generation of *E. ambiguella* from 1980 to 2022 (Ø all site clusters; for eggs/larvae only from 2002 onwards, when the branch cage method was first used).

1st generation eggs, 2nd flight adults and 2nd generation eggs (Figure 2 a-f, Table S1). As can be seen from the BIAS values indicated in Supplementary Table 1, the average deviation range extended from 0.89 days too early to 0.95 days too late.

1.2 *Eupoecilia ambiguella*

Six different MLR models for adult/egg/larvae stage of 1st and 2nd flight/generation of *E. ambiguella* were calibrated and validated. The final calibrated MLR models for *E. ambiguella* included individual weather variables for each developmental stage per flight/generation. All independent variables (= weather variables) displayed a statistically significant ($P < 0.05$) linear relationship with the dependent variable (= DOY of first seasonal occurrence of *E. ambiguella* 1st/2nd flight/generation adults/eggs/larvae). The variance inflation factor (VIF) displayed low linear connection between the input variables of each generated MLR model (Table 6).

The final MLR equations and their applied monthly or weekly calculation periods for predicting the first seasonal occurrence of *E. ambiguella* 1st/2nd flight/generation adults/eggs/larvae are presented in Table 7.

The prediction accuracies of the six *E. ambiguella* MLR models with the validation dataset were very high for 2nd flight adults, high for 1st flight adults and satisfactory for 2nd generation eggs and larvae (Figure 3 a-f; Table S3). As can be seen from the BIAS values indicated in Table S3, the average deviation range extended from 2.85 days too early to 0.20 days too late. The MLR models predicting the first seasonal occurrence of 1st generation egg and larvae could not be validated due to the insufficient number of available datasets ($n = 1$).

2. Prediction accuracies of adapted and new MLR models

The validation results of the adapted and new MLR models for *L. botrana* showed better prediction accuracies than those for *E. ambiguella*, as they were correct in 64 % to 100 % of the predictions, compared to *E. ambiguella,* with 58 % to 82 % of the predictions within the optimal deviation range (not exceeding ± 2 days for adults and ± 4 days for egg and larvae stage). The adapted and new MLR models for both grape moth species tended to predict the first seasonal occurrence too early rather than too late (Table S4).

3. Prediction accuracies of existing MLR models

The validation of the existing, preliminary MLR models for predicting the first seasonal occurrence of 1st flight adults of both grape moth species (Blümel *et al.*, 2020) was carried out with the same dataset as the adapted MLR models and resulted in a lower prediction accuracy than the adapted MLR models (Table S5).

DISCUSSION

The present study aimed to improve existing multiple linear regression (MLR) models and to generate new ones for precise, validated predictions of first seasonal occurrences of *L. botrana* and *E. ambiguella* 1st/2nd flight/generation adults/eggs/larvae. The existing MLR models for the prediction of the first seasonal occurrence of *L. botrana* and *E. ambiguella* 1st flight adults (Blümel *et al.*, 2020) were based on a restricted part of the usable monitoring data from Austria and adapted using additional monitoring data from other wine-growing regions in Austria, as well as more input parameters from two temperature sum models (Gallardo *et al.*, 2009; Carlos *et al.*, 2018) and a physiologically based demographic model (Gutierrez *et al.*, 2012). This improved the prediction accuracies of the first seasonal occurrence of *L. botrana* and *E. ambiguella* 1st flight adults by an average of 2.94 days and 0.85 days, respectively. Initial versions of the new MLR models that predict the first seasonal occurrence of *L. botrana* 1st generation eggs/larvae and 2nd generation larvae (Kolkmann *et al.*, 2024) were further improved after testing the generated MLR models for multicollinearity while applying a VIF < 4 (O'Brien, 2007).

Overall, the newly calibrated and validated MLR models for predicting the first seasonal occurrences of the different *L. botrana*/*E. ambiguella* 1st and 2nd flight/generation developmental stages resulted in very high to satisfactory prediction accuracies with regard to the statistical indicators applied in the validation and the calculated deviations between predicted and observed day of year (DOY). The generated MLR models often predicted the first seasonal occurrences of the different developmental stages per flight/generation of both grape moth species in the optimum deviation range between predicted and observed first seasonal occurrence (adults ≤ 2 days and eggs/larvae ≤ 4 days deviation). The quality and quantity of the usable monitoring data had a substantial impact on the prediction accuracy of the generated MLR models of both grape moth species. The two species differed in deviation range between predicted and observed first seasonal occurrence, which was in nearly all cases larger for the MLR models of *E. ambiguella* than for *L. botrana*. The smaller deviations for the *L. botrana* MLR models could be due to the higher number of usable datasets from a larger variety of site clusters and different wine-growing regions available for *L. botrana* model calibration and validation compared to *E. ambiguella*. The new MLR models for *L. botrana* adults/eggs/larvae were calibrated with datasets from four to seven different clusters from nine wine-growing regions, compared to datasets from two to six different clusters from six wine-growing regions for *E. ambiguella*. For the latter grape moth species, the datasets from three wine-growing regions had to be excluded from the final model calibration, as they resulted in a reduced prediction accuracy due to the small number of usable datasets. A cluster with few usable datasets and specific site conditions that differ from the other clusters implemented in the calibration does not sufficiently reflect the specific conditions in the calibration, and it ultimately has a negative impact on the prediction accuracy of the generated model. Meanwhile, a cluster that had few datasets but similar site conditions to other clusters did not show any such impact. Likewise, the quantity of monitoring datasets for the 1st generation egg and larvae stages of *E. ambiguella* was too small ($n = 1$) for the validation of the calibrated equations.

TABLE 4. Results of stepwise multiple linear regression analysis predicting the day of year of first seasonal occurrence of the different flights/generations and developmental stages of *L. botrana*.

Flight/ generation	Developmental stage	Model variables	B	SE	β	t	*P*	VIF
1st flight	adults	Intercept	136.663	2.899	-	47.139	< 0.001	-
		Tbase 6.5	-0.089	0.009	-0.801	-9.755	< 0.001	1.191
		Precip Y/N	0.191	0.073	0.214	2.612	0.014	1.191
		Note: $R^2_{adj.}$ = 0.813 (*n* = 34, *P* < 0.001).						
1st generation	eggs	Intercept	127.500	5.913	-	21.564	< 0.001	-
		Tbase 14.5	-0.190	0.039	-0.801	-4.931	< 0.001	1.352
		Rad	0.017	0.017	0.169	1.038	0.310	1.352
		Note: $R^2_{adj.}$ = 0.493 (*n* = 27, *P* < 0.001).						
	larvae	Intercept	168.993	11.498	-	14.698	< 0.001	-
		Tbase 6.5	-0.150	0.024	0.804	-6.303	< 0.001	1.122
		Precip Y/N	-0.357	0.287	-0.199	-1.244	0.223	1.768
		Rad	0.001	0.021	0.008	0.049	0.961	1.642
		Note: $R^2_{adj.}$ = 0.536 (*n* = 33, *P* < 0.001).						
2nd gflight	adults	Intercept	225.602	4.199	-	53.722	< 0.001	-
		Tbase 8	-0.069	0.005	-0.864	-14.483	< 0.001	1.082
		Precipsum	0.021	0.006	0.214	3.581	0.001	1.082
		Note: $R^2_{adj.}$ = 0.888 (*n* = 35, *P* < 0.001).						
2nd generation	eggs	Intercept	228.995	6.396	-	35.805	< 0.001	-
		Tmean ≥ 14	-1.118	0.258	-0.471	-4.327	< 0.001	1.305
		Tbase 13	-0.072	0.020	-0.401	-3.682	0.001	1.305
		Note: $R^2_{adj.}$ = 0.546 (*n* = 51, *P* < 0.001).						
	larvae	Intercept	228.750	10.063	-	22.731	< 0.001	-
		Tmean ≥ 14	-0.902	0.288	-0.315	-3.132	0.003	1.445
		Rad	0.029	0.012	0.219	2.341	0.023	1.245
		Wind	-1.903	1.028	-0.155	-1.851	0.070	1.004
		Tbase 12	-0.124	0.022	-0.616	-5.608	< 0.001	1.722
		Note: $R^2_{adj.}$ = 0.614 (*n* = 56, *P* < 0.001).						

Nomenclature: B = B-coefficient (unstandardised coefficient); SE = standard error of unstandardised coefficient; β = Beta-coefficient (standardised coefficient); t = t-statistic; P = significance; VIF = variance inflation factor; R2adj. = adjusted coefficient of determination; n = sample size.

TABLE 5. Final MLR equations and applied calculation period for the prediction of the DOY of first seasonal occurrence of 1st/2nd flight/generation adults/eggs/larvae of *L. botrana*.

MLR model for *L. botrana*	Equation	Calculation period
1st flight adults	DOY = 136.663 + (Tbase 6.5 × -0.089) + (Precip Y/N × 0.191)	1 March to 30 April*
1st gen. eggs	DOY = 127.500 + (Tbase 14.5 × -0.190) + (Rad × 0.017)	6 May to 26 May**
1st gen. larvae	DOY = 168.993 + (Tbase 6.5 × -0.150) + (Rad × 0.001) + (Precip Y/N × -0.357)	6 May to 26 May**
2nd flight adults	DOY = 225.602 + (Tbase 8 × -0.069) + (Precipsum × 0.021)	1 March to 30 June*
2nd gen. eggs	DOY = 228.995 + (Tmean ≥ 14 × -1.118) + (Tbase 13 × -0.072)	1 June to 30 June*
2nd gen. larvae	DOY = 228.750 + (Tmean ≥ 14 × -0.902) + (Rad × 0.029) + (Wind × -1.903) + (Tbase 12 × -0.124)	1 June to 30 June*

*Monthly calculation period, **weekly calculation period.

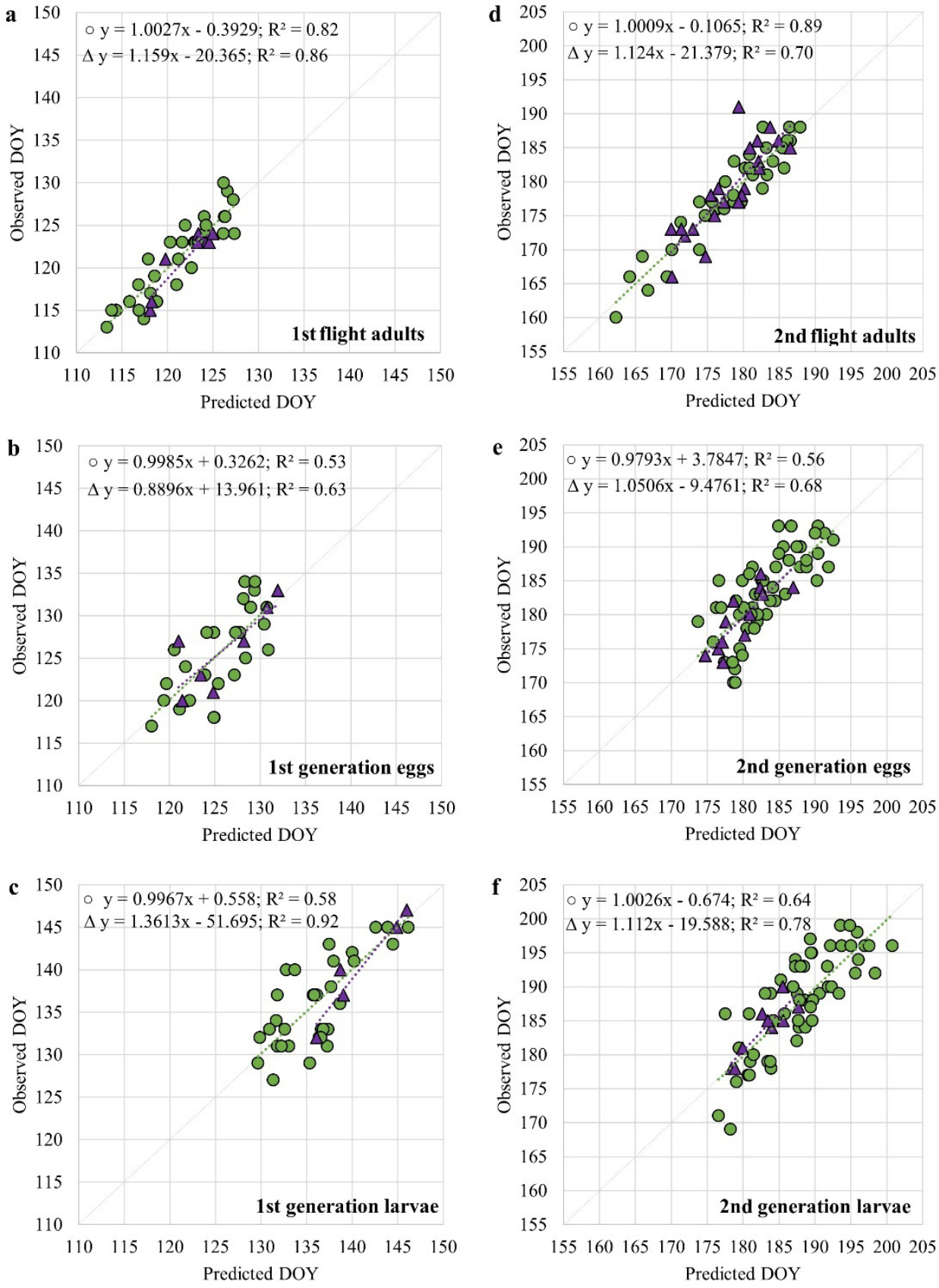


FIGURE 2. Linear regressions between observed and predicted day of year (DOY) to predict the first seasonal occurrence of *L. botrana* 1st flight adults (a), 1st generation eggs (b) and larvae (c), 2nd flight adults (d), 2nd generation eggs (e) and larvae (f), from 2002 to 2022 (○ = calibration dataset and Δ = validation dataset). Deviations above the 1:1 line indicate a too early forecast, and below the line a too late forecast.

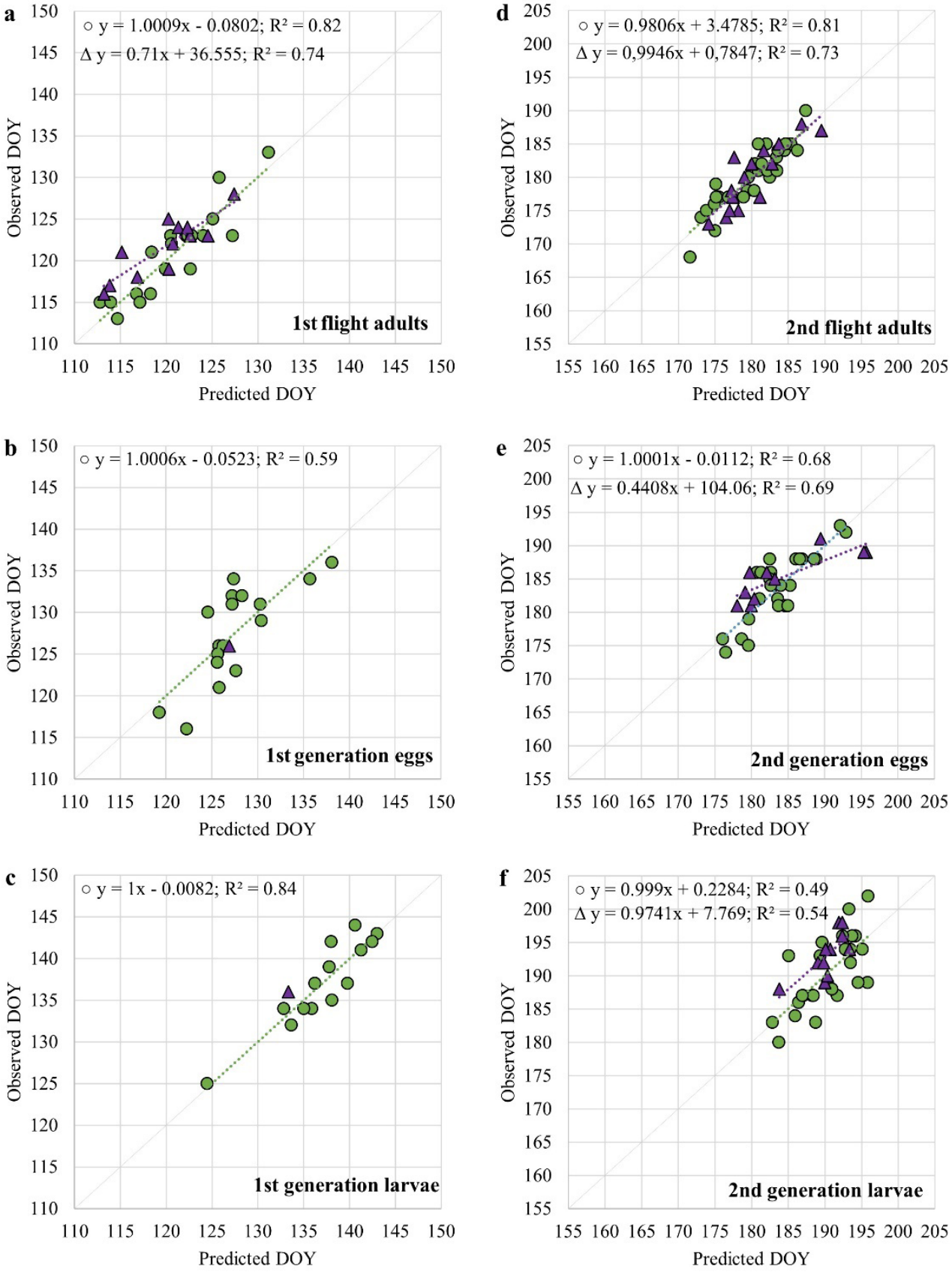


FIGURE 3. Linear regressions between observed and predicted day of year (DOY) to predict the first seasonal occurrence of *E. ambiguella* 1st flight adults (a), 1st generation eggs (b) and larvae (c), 2nd flight adults (d), 2nd generation eggs (e) and larvae (f), from 1990 to 2022 (○ = calibration dataset and Δ = validation dataset). Deviations above the 1:1 line indicate a too early forecast, and below the line a too late forecast.

TABLE 6. Results of stepwise multiple linear regression analysis predicting the day of year of first seasonal occurrence of the different flights/generations and developmental stages of *E. ambiguella*.

Flight/ generation	Developmental stage	Model variables	B	SE	β	t	P	VIF
1st flight	adults	Intercept	145.059	3.672	-	39.503	< 0.001	-
		Tmean	-3.314	0.407	-0.866	-8.139	< 0.001	1.005
		Precipsum	0.052	0.017	0.336	3.159	0.006	1.005
		Note: $R^2_{adj.}$ = 0.797 (*n* = 19, *P* = < 0.001).						
1st generation	eggs	Intercept	80.708	10.585	-	7.624	< 0.001	-
		Precip Y/N	-1.587	0.569	-0.684	-2.787	0.015	2.038
		RH	0.881	0.199	1.085	4.422	0.001	2.038
		Note: $R^2_{adj.}$ = 0.527 (*n* = 17, *P* = 0.002).						
	larvae	Intercept	62.661	10.806	-	5.799	< 0.001	-
		RH	1.143	0.172	0.817	6.659	< 0.001	1.046
		Tmean < 6	0.550	0.243	0.279	2.270	0.044	1.046
		Note: $R^2_{adj.}$ = 0.813 (*n* = 14, *P* = < 0.001).						
2nd flight	adults	Intercept	197.183	7.399	-	26.651	< 0.001	-
		Tbase 8	-0.025	0.007	-0.404	-3.692	0.001	1.573
		Precip Y/N	0.228	0.048	0.473	4.788	< 0.001	1.282
		Rad	-0.006	0.002	-0.273	-2.721	0.012	1.324
		Note: $R^2_{adj.}$ = 0.795 (*n* = 28, *P* = < 0.001).						
2nd generation	eggs	Intercept	295.017	19.427	-	15.186	< 0.001	-
		Tmin	-1.092	0.274	-0.475	-3.983	0.001	1.039
		Tmean ≥ 14	-6.479	1.357	-0.600	-4.776	< 0.001	1.153
		Wind	-2.619	0.874	-0.376	-2.996	0.006	1.148
		Note: $R^2_{adj.}$ = 0.644 (*n* = 27, *P* = < 0.001).						
	larvae	Intercept	227.998	8.498	-	26.830	< 0.001	-
		Tbase 7.5	-0.080	0.023	-0.531	-3.489	0.002	1.049
		Wind	-2.928	1.250	-0.357	-2.342	0.028	1.049
		Note: $R^2_{adj.}$ = 0.447 (*n* = 26, *P* = < 0.001).						

Nomenclature: B = B-coefficient (unstandardised coefficient); SE = standard error of unstandardised coefficient; β = Beta-coefficient (standardised coefficient); t = t-statistic; *P* = significance; VIF = variance inflation factor; R^2adj. = adjusted coefficient of determination; *n* = sample size.

TABLE 7. Final MLR equations and applied calculation period for the prediction of the DOY of first seasonal occurrence of 1st/2nd flight/generation adults/eggs/larvae of *E. ambiguella*.

MLR model for *E. ambiguella*	Equation	Calculation period
1st flight adults	DOY = 145.059 + (Tmean × -3.314) + (Precipsum × 0.052)	1 March to 30 April*
1st gen. eggs	DOY = 80.708 + (RH × 0.881) + (Precip Y/N × -1.587)	15 April to 28 April**
1st gen. larvae	DOY = 62.661 + (RH × 1.143) + (Tmean < 6 × 0.550)	1 April to 31 May*
2nd flight adults	DOY = 197.183 + (Tbase 8 × -0.025) + (Precip Y/N × 0.228) + (Rad × -0.006)	1 January to 30 June*
2nd gen. eggs	DOY = 295.017 + (Tmin × -1.092) + (Tmean ≥ 14 × -6.479) + (Wind × -2.619)	1 June to 14 June**
2nd gen. larvae	DOY = 227.998 + (Tbase 7.5 × -0.080) + (Wind × -2.928)	1 June to 30 June*

*Monthly calculation period, ** weekly calculation period.

With regard to the applied monitoring methods, the branch cage method (Polesny *et al.*, 2000), which was used from 2002 onwards, provided real-time monitoring data for all considered developmental stages of both flights/generations of the two grape moth species. However, because the starting pupae material was from naturally occurring specimens collected in the field, it was sometimes not possible for enough individuals from each grape moth species of each flight/generation, developmental stage and monitoring year to be collected; this resulted in partly missing data and a reduced number of usable datasets. The monitoring data obtained using pheromone traps - whose efficiency is often affected by the prevailing environmental conditions (Baumgärtner *et al.*, 2012) and which were exclusively applied during the first two decades of the long-term observations–only show the catches of male adults but do not allow the precise date of first seasonal occurrence of adult females to be determined (Hoppmann and Holst, 1990). This is due to the protandry of the males occurring about two to five days earlier than the females (Gabel and Mocko, 1984), which leads to an erroneously premature reporting of the first occurrence of the females as the relevant adult stage for population development. In addition, the trap catches were not recorded daily, but with a two- to three-day interval, as the monitoring data were retrieved from routine observations to advise winegrowers on control measures. During the preparation of the monitoring data, these difficulties were all considered. To ensure the usability of the pheromone trap monitoring data for the subsequent MLR analysis and model generation, it was necessary to meet three quality requirements: i) a 0-catch observation before the initial first occurrence to ensure that the first seasonal occurrence was not missed in the case of a late control of the pheromone trap, ii) an unambiguous allocation of catches to either the 1st or the 2nd flight adults, and iii) the continuous recording of all catches during the complete observation period. As well as the monitoring method and the application of the defined quality criteria for the monitoring data, the observation periods from which the datasets originated also had an influence on the number of usable datasets for model generation. The inclusion of datasets from the earlier monitoring decades (1980 to 2000) decreased the quality of several generated model equations, except for the MLR model predicting the first seasonal occurrence of *E. ambiguella* 1st flight adults. Therefore, the more recent datasets from the year 2000 onwards were mainly used for the final model generation, thus taking into account the growing influence of global warming in Austria since the beginning of the century (GeoSphere Austria, 2024) and the predominant use of the branch cage method for monitoring.

Besides the described impacts on the usability of the monitoring data, the measured weather data from the reference weather stations displayed some shortcomings caused by gaps in the measurements. The availability and accuracy of measured weather data could affect the application and performance of forecasting models (Heit *et al.*, 2019). Therefore, the measured weather data in this study was checked for plausibility, and the data gaps were filled with data from the Spatiotemporal Reanalysis Dataset for Climate in Austria (GeoSphere Austria, 2022). However, as well as gaps in the weather data, differences between the measured weather data from a weather station and the on-site weather and microclimatic conditions (Baumgärtner & Baronio, 1988) could also lead to prediction outliers. In the present study, the prevailing microclimate of the individual observation sites did not always match the measured weather data of the reference weather stations; this can be attributed to large distances between the reference weather stations and the corresponding observation sites, or to differences in elevation and orographic conditions, which could probably not be fully compensated for by the elevation corrections.

Although the generated MLR models were based on a large number of weather parameters and monitoring datasets, it was not possible to include other parameters in the modelling, which could explain some of the prediction outliers. These parameters were mainly biotic and comprised, for example, host plants or natural enemies that affect the life cycle, pest phenology and population dynamics of *L. botrana* (Ainseba *et al.*, 2011; Thiéry *et al.*, 2014; Gilioli *et al.*, 2016). Host plants can have a major impact on the development duration, degree of protandry, sex and size ratio and fecundity of *L. botrana* depending on grape variety and berry stage (*e.g.*, inflorescence or maturing fruit) (Torres-Vila *et al.*, 2005; Moreau *et al.*, 2006; Thiéry *et al.*, 2014; Gilioli *et al.*, 2016; Gutierrez *et al.*, 2012; Gutierrez *et al.*, 2018). Despite the described uncertainties in the obtained prediction results, the generated MLR models could be implemented in advisory systems. Prediction models can only achieve a reasonable level of accuracy (Damos & Savopoulou-Soultani, 2012; Gutierrez *et al.*, 2018), an empirical model can never completely reproduce the life cycle of a pest and all its complexity, such as delay processes with time-varying effects of various parameters (Manetsch, 1976) and the unknown impact of additional factors (Schmidt *et al.*, 2003). Although there are many unknown factors, it has already been proven that several weather parameters can have an impact on the life cycle of *L. botrana* and *E. ambiguella,* either alone or in combination.

Temperature is one of the abiotic factors to have the most influence on the development of both these grape moth species (Bovey, 1966), affecting the developmental speed of different developmental stages per generation and gender depending on lower and upper temperature thresholds (Gabel, 1981; Briere *et al.,* 1999). In this study, the weather parameter daily mean air temperature nearly always had the greatest impact on the first seasonal occurrence of the different developmental stages per generation of both grape moth species. Thus, all generated MLR models consisted of at least one weather variable processed from the weather parameter daily mean air temperature, except for the MLR model for 1st generation eggs of *E. ambiguella*, which achieved satisfactory prediction accuracies without including a temperature variable.

Weather parameter precipitation has been described as being associated with both the dispersal ability of *L. botrana*

(Rank *et al.*, 2020; Zumbado-Ulate *et al.*, 2023) and its mortality rate (Schmidt *et al.*, 2001). In this study, the data provided by the daily precipitation measurements was processed into two different precipitation variables. Six of the twelve final MLR equations included one of the processed daily precipitation variables.

Four MLR equations included the weather variable daily global radiation. The effect of global radiation on the life cycle of *L. botrana* and *E. ambiguella* has not yet been sufficiently investigated, but the inclusion of this variable improved the prediction accuracies of the generated MLR models (the prediction made with the validation dataset displayed an improvement in accuracy by 3.06 days and 0.83 days for *L. botrana* and *E. ambiguella* 1st flight adults, respectively). Instead of global radiation, the effect of sun exposure and photoperiod on the life cycle of *L. botrana* were investigated. Sun exposure affects the timing of egg hatching (Moosavi *et al.*, 2018) and the photoperiod can impact the diapause induction and larval development (Deseö *et al.*, 1981; Pavan *et al.*, 2013) of *L. botrana*.

Relative humidity can have an impact on the spatial and geographical distribution of both *L. botrana* and *E. ambiguella*, as the density of their populations is largely affected by prevailing relative humidity levels (Bovey, 1966). *E. ambiguella* is more sensitive to lower humidity levels than *L. botrana* (Bovey, 1966), and its spread to dry wine-growing regions in Southern Europe could therefore be restricted (Bovey, 1966). As relative humidity and temperature can have an effect on the egg stage until the hatching of larvae (Götz, 1941), the weather parameter daily relative humidity was also included in the final MLR models that predicted first seasonal occurrence of *E. ambiguella* 1st generation eggs and larvae, which displayed satisfactory prediction accuracies ($R^2 > 0.5$, RMSE < 4.5, | BIAS | < 3.0).

High wind speed can affect the flight activity of adult moths (Di Silvestro *et al.*, 1999) and indirectly affect fertility rate by delaying copulation (Schmidt *et al.*, 2001). The inclusion of the daily wind speed variable in the equations of three MLR models improved the prediction accuracy of the calibration dataset by 0.15 to 0.68 days.

Although the range of effects of each of the weather parameters and the correlations between them have not yet been sufficiently investigated (Schmidt *et al.*, 2001), various correlations between weather parameters and their joint effects on certain parts of the life cycle of *L. botrana* and *E. ambiguella* have been identified. For example, the survival rate of *L. botrana* and *E. ambiguella* was found to be influenced by a combination of wind speed, relative humidity and precipitation (Schmidt *et al.*, 2001). Furthermore, pupal diapause is known to be affected by both temperature and photoperiod (Roditakis & Karandinos, 2001; Baumgärtner *et al.*, 2012; Castex *et al.*, 2020), and a combination of temperature, precipitation and wind speed to impact the flight activity of *E. ambiguella* and *L. botrana* (Russ, 1966; Di Silvestro *et al.*, 1999). Various studies have found a correlation between the flight activity of both of the grape moth species and relative humidity in combination with temperature and development rate (Bovey, 1966; Hoppmann & Holst, 1990; Briere & Pracros, 1998; Schmidt *et al.*, 2003; Amo-Salas *et al.*, 2011). Additionally, the geographical and spatial distribution of *L. botrana* is influenced by the combined effects of temperature, precipitation and elevation (Rank *et al.*, 2020; Zumbado-Ulate *et al*., 2023). *L. botrana* prefers hot and dry weather conditions, whereas *E. ambiguella* prefers colder hilly sites and humid weather conditions (Bournier, 1976; Kehrli *et al.*, 2014; Comșa *et al.*, 2022). The geographical elevation of a site has a strong effect on the first seasonal occurrence of both grape moth species, with sites at lower elevations being favoured by *L. botrana* and those at higher elevations by *E. ambiguella* (Comșa *et al.*, 2022).

In Austria, *L. botrana* originally occurred mainly in wine-growing regions of warm weather conditions and low elevations (Höbaus, 1988). At present, mixed populations of *L. botrana* and *E. ambiguella* occur in almost all wine-growing regions of Austria with varying annual composition. Therefore, a calibration and validation of joint MLR models for both of the grape moth species was initially considered, but eventually discarded when it became apparent how much their population dynamics deviated depending on monitoring site and year in Austria. This divergence could be explained by the two species' differing preferences in terms of biotic (*e.g.*, grape variety) and abiotic factors (*e.g.*, climatic conditions) (Comșa *et al.*, 2022). Thus, separate prediction models were generated for each of the two grape moth species. The multiple linear regression analysis was selected for the model generation in this study, because it allowed all available input data to be included and processed, and the relationship between one dependent variable and multiple independent variables to be simultaneously assessed. MLR models developed for other pests (*e.g.*, *Helicoverpa armigera*, aphids and thrips) have achieved reasonable results when predicting the date of first seasonal occurrence (Aswathi & Duraisamy, 2018; Balikai, *et al.*, 2019).

A prediction model based on only one variable (*e.g.*, temperature sum model) does not consider other potentially influencing variables, which could have a negative impact on model performance (Russ, 1966; Gilioli *et al.*, 2016). The inclusion of more than one relevant weather variable in a mathematical model was found to improve prediction accuracy relative to prediction models that only consider one weather variable (Blümel *et al.*, 2020; Balduque-Gil *et al.*, 2023). The consideration of two to several different variables that influence the life cycle of *L. botrana* and *E. ambiguella* can result in models with higher prediction accuracies, a higher variety of output information (*e.g.*, abundance, distribution and first occurrence) and different scales of model implementation (regional or global) (Ainseba *et al.*, 2011; Amo-Salas *et al.*, 2011; Damos & Savopoulou-Soultani, 2012).

Due to the importance of using several different influencing weather parameters to generate models that produce high prediction accuracies, the present study included various weather variables in the stepwise MLR analysis, which

automatically filtered the most relevant weather variables for predicting the first seasonal occurrence of 1st/2nd flight/generation adults/eggs/larvae of *L. botrana*/*E. ambiguella*. Furthermore, the test for multicollinearity ensured that each weather variable included in the final MLR models had an independent effect on the respective first seasonal occurrence. The variables processed from the weather parameter mean air temperature are those implemented most in the final MLR models, followed by the variables processed from the weather parameters daily precipitation, daily global radiation, daily wind speed, daily relative humidity and daily minimum air temperature. Each final calibrated and validated MLR model consisted of different weather variables with varying influence on the dependent variable (DOY of pest observation).

For the different developmental stages of *L. botrana* and *E. ambiguella* per flight/generation, individual MLR models were generated using weather variables and calculation periods specifically assigned to the various development stages. Therefore, the problem of inconsistency in the predictions of subsequent pest generations was avoided in the generated MLR models; this problem can occur when a model predicts complete population dynamics and when subsequent forecasts depend on preceding forecasts (Schmidt *et al.*, 2003).

It should be noted that the developed MLR models presented in this study are based on regional data that are specific to Austrian vineyards. After additional testing or re-calibration, they could also be applicable in other countries with similar climate and site conditions to those prevailing in Austria and the availability of the weather parameters applied in the MLR models. In Austria, the generated MLR models could be used to improve the current monitoring and advisory activities and could be incorporated into real-time forecasting systems for *L. botrana* and *E. ambiguella*.

The future monitoring and control of *L. botrana* and *E. ambiguella* will involve new challenges due to climate change, with for example, a possible shift of insect pest populations northward and to higher elevations (Svobodová *et al.*, 2014; Pétremand *et al.*, 2017; Castex *et al.*, 2018; Gutierrez *et al.*, 2018). Besides the application in pest forecasting, the validated MLR models for *L. botrana* and *E. ambiguella* will be also implemented in programmes that simulate future crop and land-use potentials in Austria under various future climate scenarios. The use of MLR models in the future risk assessment of the first seasonal occurrence of both of the grape moth species in Austria, could be more significant for *L. botrana* than for *E. ambiguella*, as the former species is more favoured by climate warming (Pétremand *et al.*, 2017).

CONCLUSION

The generated multiple linear regression (MLR) models for predicting the first seasonal occurrence of the different developmental stages per flight/generation of *L. botrana* and *E. ambiguella* displayed high to satisfactory prediction accuracies. For *L. botrana* adults/eggs/larvae of the 1st and 2nd flight/generation, the validated MLR models resulted in predictions that were on average 0.89 days too early to 0.95 days too late; meanwhile, for *E. ambiguella* they were on average 2.85 days too early to 0.20 days too late. The two adapted and ten newly generated MLR models could help improve the planning of labour- and time-consuming monitoring activities for a timely implementation of pest control measurements, and could therefore be implemented within the real-time forecasting systems of the Austrian advisory services. In addition, for the future risk assessment of *L. botrana* and *E. ambiguella* infestation in Austrian vineyards, the validated equations will be implemented in simulations of future crop land-use potentials and infestation hotspots under local climate change scenarios. In the future, MLR models will have to be adapted to the increasing number of extreme weather events and the mostly unknown responses of pests to them by incorporating additional monitoring data.

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