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Development of a Predictive Model of the Flight Dynamics of the European Corn Borer, *Ostrinia nubilalis* Hübner, 1796 (Lepidoptera: Pyralidae), in the Vojvodina Region, Serbia—Implications for Integrated Pest Management

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Abstract: Although corn production is affected by several harmful insects, its most important pest in the southeastern region of Europe is the European corn borer (ECB), *Ostrinia nubilalis* Hübner, 1796 (Lepidoptera: Pyralidae). Chemical control of *O. nubilalis* remains the main strategy in conventional corn production. The key to successfully achieving a high efficiency of insecticides is determining the appropriate moment of application, including the exact time in the insect's life cycle when it is most vulnerable. In this study, monitoring data on the flight dynamics of ECB adults from a seven-year period (2014–2020) were exploited for the development of a predictive model of adult numbers within the growing season. ECB monitoring was performed by using light traps at 15 different locations in the Vojvodina region (Serbia) during the specified time period. First, the calendar for Vojvodina was created based on the analytics of the collected monitoring data. Additionally, the calendar was converted to the probability of ECB occurrence during the growing season, specifying the time interval between the appearance of each generation of the pest. Second, using machine learning techniques, a phenological model was designed that included daily values of relevant meteorological features, such as cumulative degree-days, relative humidity, and precipitation. The calendar had a lower prediction error when compared to the phenological model, and it was tested as a supporting management tool for the ECB in 2021, with a root-mean-square error of the number of adults of 46.67. Such an approach could significantly reduce both the consumption of insecticides and the number of chemical treatments, respectively. Above all, this approach has broad potential in IPM and organic farming, and it is fully compatible with biological control methods.

Keywords: *Ostrinia nubilalis*; insect phenology; corn; predictive model; weather data

1. Introduction

Large corn areas are very favourable for the mass reproduction of specific pests of corn, which are trophically closely related to this crop [1]. In Serbia, corn is endangered by 130 different harmful organisms, with insects causing the most total damage (70%) [2,3]. Although the production of corn is affected by several harmful insects, the most important pest of corn in Southeast Europe (SEE) is the European corn borer (ECB), *Ostrinia nubilalis* Hübner, 1796 (Lepidoptera: Pyralidae) [4,5]. The ECB is a highly polyphagous pest that can reproduce on many host plants. However, in this part of Europe, the preferred host is corn, and the large-scale cultivation of corn has contributed to the rapid spread of the ECB over large areas [6]. The corn borer causes damage in the larval stage, which occurs as larvae feed on the leaves and bore into corn stalks and ear shanks. This type of damage disrupts assimilate translocation throughout the plant, introduces pathogens, and, most importantly, reduces the quantity and quality of yield [7–9]. Damages from the first generation of the ECB, specific to the initial stages of corn growth, are less significant, while pest activity during the flowering stage and grain fill period can considerably damage plants and directly reduce corn yields [6,10,11]. The annual report of the Forecasting and Reporting Service for Plant Protection of Serbia indicates that the intensity of ECB attacks in Vojvodina in the period from 2014 to 2021 ranged between 30 and 50%, depending on the locality and date of examination (www.pissrbija.com) (accessed on 20 December 2022). In eastern Croatia, an area with similar agro-climatic conditions, the average intensity of ECB attacks was 37% over a period of 25 years (1971–1996) [12], and in the last ten years, the intensity of attacks was between 90 and 100% [13].

The European corn borer is a holometabolous insect, and each generation consists of four phenological stages: egg, larva (five instars), pupa, and adult. This insect overwinters in corn field debris as a diapausing fifth instar larva [14]. The ECB diapause termination is controlled by the length of the scotophase (the dark photoperiodic phase) and temperature, with the latter having secondary importance [15]. According to the studies of Skopik and Bowen [16], diapause termination starts after 4 days with the scotophase lasting less than 10 h. In the region of Vojvodina (Serbia), the scotophase lasts less than 10 h on the 25th of April (https://gml.noaa.gov/ accessed on 20 December 2022). The number of generations of ECB can vary from one to five, depending on climate and genetic factors [17]. In Serbia, the number of generations varies from two to three in warmer years [6,11]. According to agricultural practice in Serbia, the activity of the first and second generations of adults is usually monitored to manage the treatments against this insect. In recent years, especially in the production of sweet corn and corn for seed, the activity of the third generation of the ECB has also been intensively monitored. Therefore, the modelling approach used in this paper considered the biological development of *O. nubilalis* from diapause termination to the adult flight of the third generation.

Methods that have been suggested for the control of ECB population and damage include the planting of genetically engineered corn hybrids, tolerant hybrids [18], crop techniques such as shredding and ploughing, and chemical treatment by means of self-powered spraying machines applying organophosphates and pyrethroids [19–21]. In SEE conventional corn production, chemical methods represent the main strategy for controlling ECB damage. The application of insecticides is most often carried out as curative measures, meaning that they are applied when the larvae have not yet bored into the corn stalk [22]. Therefore, the best period for a single application is when most of the ECB population is in the egg hatching phase, which should be between 10 and 14 days after the initiation of egg laying, i.e., 0–4 days after the adult flight peak [17]. Chemical control of *O. nubilalis* in corn is a very demanding task because the effectiveness of treatment depends on several factors, such as the overlapping of the ECB generations (which can be seen at the web portal of the Forecasting and Reporting Service for Plant Protection of Serbia), a long period of female oviposition, a short period of exposure of larvae to chemical agents, and difficult application in full vegetation. Farmers equipped with appropriate machinery (drones, high-clearance sprayers) often relieve the effect of the aforementioned obstacles by increasing the number of chemical treatments, which is contrary to the basic principles of integrated pest management (IPM) [23]. The key to achieving high efficiency of applied insecticides is determining the best time to apply them. According to Maiorano [24], the timing of the chemical treatment is critical to the IPM of the ECB.

Forecasting and determining the optimal moment to implement curative measures in order to control the ECB is a very complex task and represents an essential prerequisite for the successful protection of corn. To achieve the desired goals, it is necessary to understand not only the biology of the pest, but also the impact of all environmental factors that are specific to a particular ecosystem. In practice, the most frequently used methods for ECB monitoring and predicting the occurrence of certain developmental stages of pests are the visual inspection of corn plants to determine the oviposition period and the number of newly hatched larvae, as well as the use of light or pheromone traps to monitor the flight dynamics of ECB adults. In SEE, monitoring of the ECB adult flight is usually achieved by light traps, which give an estimation of the start and peak of adult flight activity [4]. Many biotic and abiotic factors influence the appearance and intensity of ECB attacks, with weather conditions being the most significant [25]. Among them, daily temperatures and precipitation play a very important role in the ECB population dynamics [26]. Many researchers have attempted to create models based on climatic factors in order to predict pest occurrences more precisely, monitor pests, and apply appropriate control measures [27,28]. These models aim to predict the time of occurrence of biological events, such as the appearance of specific insect pest phenological stages. Certain models make use of the fact that the development of insects such as the ECB depends on the ambient environmental temperature, and such models are usually based on degree-day accumulation [17,27,29,30]. In various research areas, bio-calendars represent the simplest observational approach for predicting the time of occurrence of specific phenomena. Considering that the biological development and flight dynamics of the ECB are directly linked to its seasonal variability, creating a phenological calendar using big data analytics can predict the time of occurrence of this pest.

The objective of this study was to develop a pest prediction model based on the daily number of ECB adults measured in the Vojvodina region of Serbia. First, a calendar was created using big data analytics. Second, using machine learning techniques, a phenological model was designed that included daily values of relevant meteorological features, such as cumulative degree-days, relative humidity, and precipitation. Since the calendar provided better results by having a lower prediction error, its potential use as a supporting management tool for one of the most important corn pests in Europe was tested for the year 2021.

2. Materials and Methods

2.1. Study Area

Vojvodina is the northern region of Serbia, located on the southern part of the Pannonian Plain and the southeastern part of the European continent, with a total surface area of 2,150,600 ha (Figure 1). It is characterised by intensive agriculture since 83% of the territory is agricultural land, most of which is cropland (around 77%). The climate of Vojvodina is moderately continental, with cold winters and hot and humid summers, a mean annual temperature of 11.1 °C, and a mean annual precipitation of 606 mm [31].

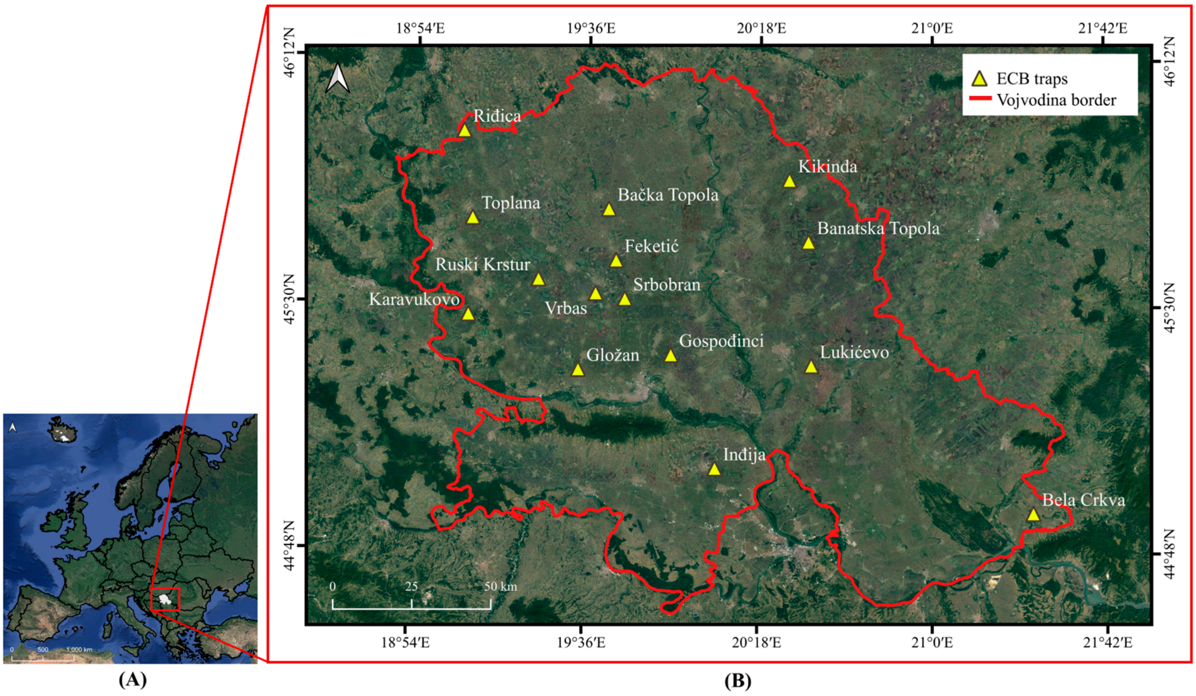

Figure 1. The study area in Southeast Europe (**A**) and the location of the European corn borer (ECB) traps (**B**).

2.2. Dataset

In the period from 2014 to 2020, the dynamics of ECB adult flight were monitored by light traps set at 15 different locations in the territory of Vojvodina (Table 1). Incandescent light traps (produced by Žica DOO, Serbia) were used, with light bulbs placed at a two-metre height (Figure 2). This method was chosen because it is the most widely used method of moth monitoring [32]. The traps were activated in the evening hours (at dusk) and switched off in the morning (at dawn). The number of ECB adults was counted on a daily basis from the beginning of April to the end of September. Monitoring of the ECB adult dynamic is crucial for distinguishing the number of generations of the pest during the season and determining the period of the most intense activity of adults, during which the most intense oviposition of females occurs. Seasonal monitoring of the ECB was carried out as part of the authors' collaboration with the Forecasting and Reporting Service for Plant Protection of Serbia. Data collected in 2021 were used for validation.

Table 1. Location of the ECB traps and automated weather stations (AMSs).

Locality	Latitude	Longitude	AMS	Latitude	Longitude
Ruski Krstur	45.5761	19.4044	Ruski Krstur	45.5544	19.4162
Srbobran	45.5231	19.7553	Srbobran	45.5536	19.7998
Feketić	45.6319	19.7179	Zobnatica	45.8525	19.6645
Bela Crkva	44.9171	21.4060	Bela Crkva	44.8858	21.4218
Kikinda	45.8640	20.4190	Kikinda	45.8283	20.4653
Lukićevo	45.3370	20.5117	Zlatica	45.3871	20.5808
Banatska Topola	45.6887	20.4981	Banatska Topola	45.8333	20.3167
Vrbas	45.6778	19.3389	Ruski Krstur	45.5544	19.4160
Toplana	45.7472	19.1325	Toplana	45.7510	19.1372
Bačka Topola	45.7776	19.6855	Zobnatica	45.8525	19.6645
Karavukovo	45.4729	19.1229	Toplana	45.7510	19.1372
Riđica	45.9936	19.0908	Riđica	45.7937	19.3317

Gložan	45.3211	19.5704	Despotovo	45.4658	19.5729
Gospođinci	45.3649	19.9441	Kać	45.2780	19.9304
Inđija	45.0437	20.1257	Novi Slankamen	45.1412	20.2136

Figure 2. A light trap used to monitor ECB flight dynamics.

Daily values of meteorological data, such as air temperature (°C), relative humidity (%), and precipitation (mm), were collected using automated weather stations (AMSs) produced by Pessel Instruments GmbH, Weiz, Austria, from the observing network of the Forecasting and Reporting Service for Plant Protection of Serbia. Since all the stations are in the same climate type (moderate continental), with similar temperature and precipitation regimes, a missing value of a specific variable on a specific day and for a specific station was interpolated by using the proper value from the closest station. There were no long periods of missing meteorological data such as years or months, but rather days with temporary malfunction of the sensors.

2.3. Model Development

Data analytics was performed in Python, using libraries such as pandas, numpy, sklearn, and matplotlib. Annual data, including both ECB adult numbers and meteorological data, were considered during the summer half-year (April–September) i.e., the day of the year was in the interval from 92 to 274.

In aerobiology, the pollen calendar represents a basic method for predicting daily pollen concentrations of a particular plant species, and it is obtained from observations [33]. In this study, the same approach was applied. The ECB calendar was calculated as a mean value of the number of adults rounding to the closest integer, for a specific day of the year, using available data from all locations and years. For each year, the annual profile was calculated in the same way. The sum of the values in the annual profile was considered the integral for the specific year. Additionally, the calendar values were normalised to the maximum value, giving results in the range of 0 to 1, and the rolling mean with a seven-day window was used to smooth the variations. In this manner, the probability of ECB occurrence was calculated for each day.

A phenological model for predicting the daily number of adults, considering the day of the year and local meteorological conditions, was built using the Random Forest (RF) regressor [34], a very popular machine learning technique for regression problems in agriculture [35]. The total number of samples was 16,481. However, adult number values above the 97th percentile were considered outliers and were thus omitted from training the model, leaving 16,151 samples. Meteorological conditions were represented with the daily values of relevant features, such as cumulative degree-day (CDD), relative humidity, and precipitation. Cumulative degree-days present heat accumulation above a specified threshold over a defined period of time [24]. This feature was calculated as the cumulative sum for each day of the considered period, starting from the 92nd day of the year, using the following equation:

$$CDD_n = CUMSUM[(T_{mean} - T_{base})_n] \quad (1)$$

where n is the day of year, T_{mean} is the daily mean temperature, and T_{base} = 10 °C [17]. By definition, the difference in Equation (1) was replaced with zero in the case of a negative value. Hyperparameters of the RF regressor were tuned using randomised search, and the optimal values of hyperparameters were as follows: the number of trees in the forest, n_estimators = 200; the maximum depth of the tree, max_depth = 5; the number of features to consider when searching for the best split, max_features = 'sqrt'; the minimum number of samples required to be at a leaf node, min_samples_leaf = 2; and the minimum number of samples required to split an internal node, min_samples_split = 10.

When training the phenological model, 10-fold cross-validation was performed, and the results were averaged [36]. Validation of both the calendar and the phenological model was performed using the root-mean-square error (RMSE), which quantifies the amount of error and is sensitive to outliers.

3. Results

The first-ever calendar of the ECB for the Vojvodina region was created using big data analytics. The presence of the first, second, and third generation of adults can be clearly observed from the calendar (Figure 3). The peak of the first generation appears in the middle of June while the peak of the second generation appears in the beginning of August. The maximum number of adults during the summer is registered at the peak of the second generation, and it is approximately four times larger than the maximum of the first generation.

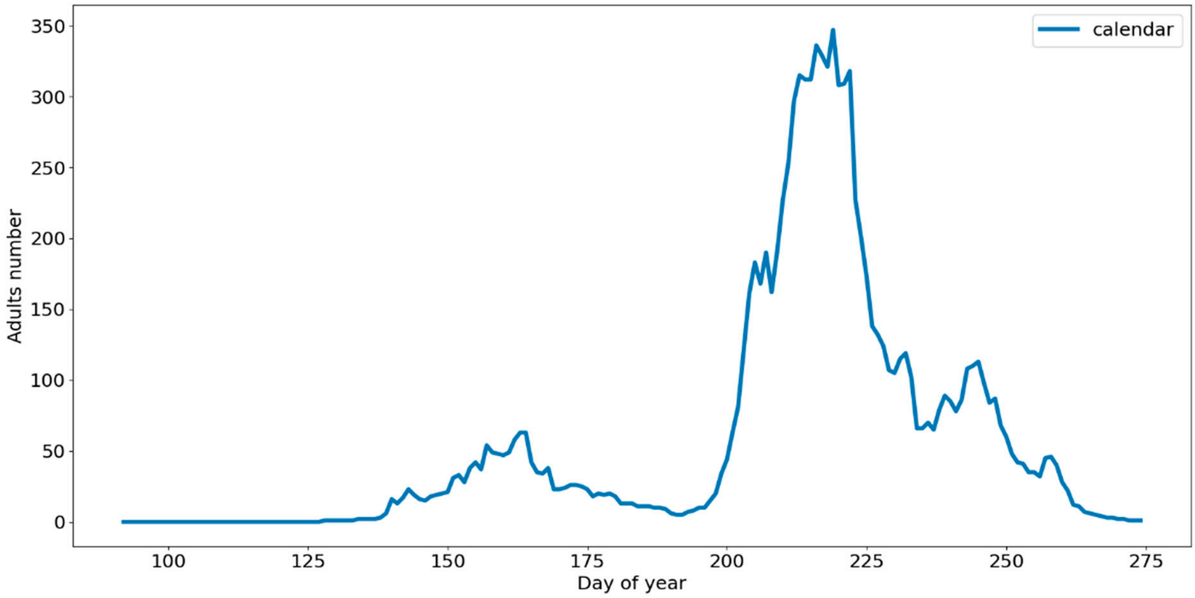

Figure 3. The ECB calendar for Vojvodina.

The appearance of ECB adults in Vojvodina begins in the first half of May, and thus the first generation can be expected to fly in June. The flight of the second generation occurs between the second half of July and the first half of August, while the third generation, if present, is recorded in early September (Figure 4).

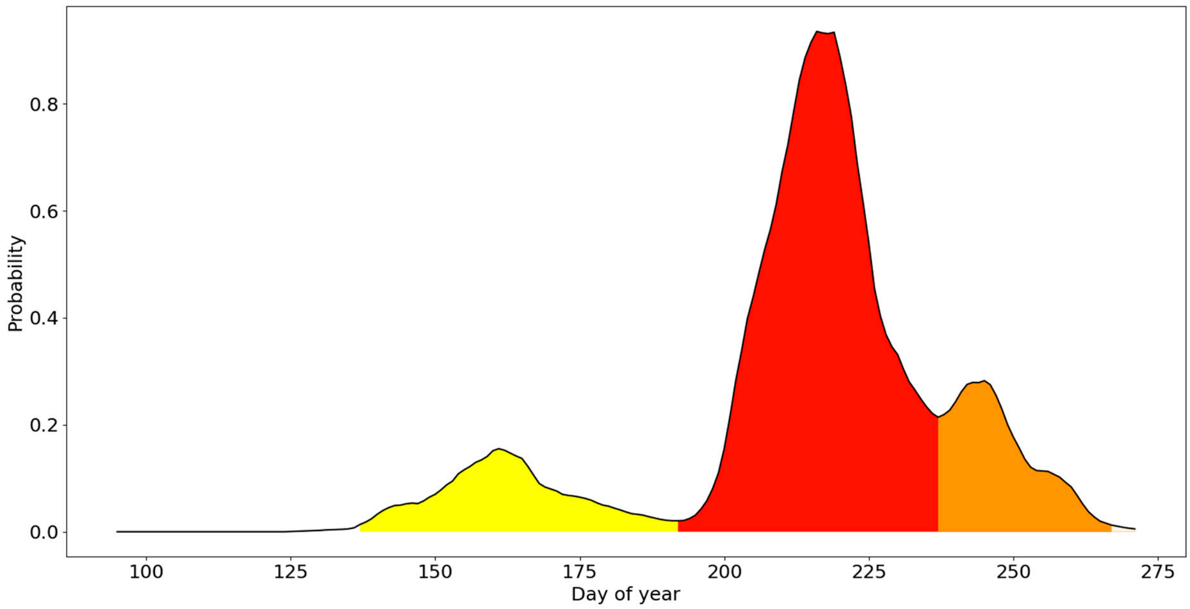

Figure 4. The probability of ECB occurrence and the expected time periods of the first (yellow), second (red), and third (orange) generations of adults.

According to Table 2, the RMSE of the prediction for a specific year was not associated with the integral of the annual profile; for example, in 2014, the integral was 9979, with RMSE of 32.30, whereas in 2017, the integral was 6550, with RMSE of 65.27. It is more likely that the RMSE was influenced by both the timing of occurrence and the number of adults during the summer, as is shown in Figure 5, particularly for the years 2016, 2015, and 2020, which have a very high RMSE.

Table 2. The integral of the annual profiles and RMSE values when compared with the calendar.

Year	Integral	RMSE
2014	9979	32.30
2015	13,942	71.26
2016	11,881	69.09
2017	6550	65.27
2018	7205	54.75
2019	8861	41.23
2020	13,469	125.28

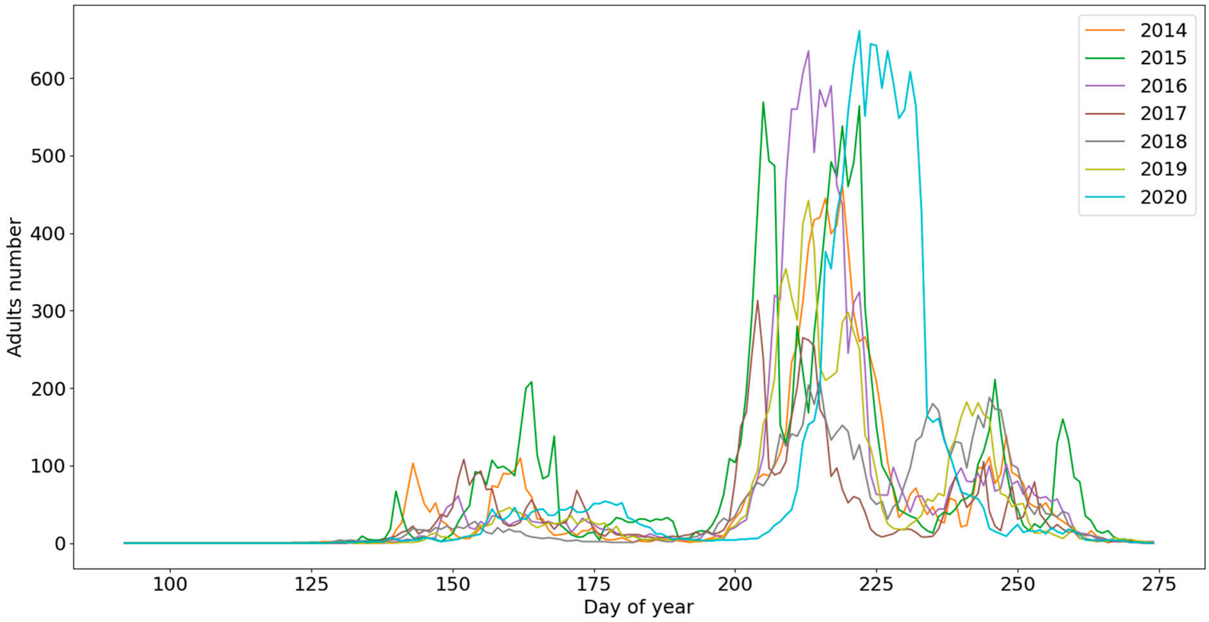

Figure 5. The annual ECB profiles for specific years.

For the phenological model, based on the Random Forest regressor, the coefficient of determination was R^2 = 0.41, with RMSE = 55.48. Before the outliers were omitted from training the model, RMSE = 142.6 was achieved. The feature importance of the RF regressor showed the following contributions to the prediction: day of year, 0.612; cumulative degree-day, 0.356; relative humidity, 0.028; and precipitation, 0.003. By definition, the sum of all contributions equals 1. As a result, the day of year was identified as the most important feature for the predictive model. Cumulative degree-day was not a particularly informative feature, since, for example, 1000 °C day^{-1} can result in a low, medium, or high number of adults (Figure 6). In addition, there is a wide interval of values, ranging approximately from 850 to 1250 °C day^{-1}, which corresponds to a very large number of adults. The contributions of both relative humidity and precipitation were negligible due to the very low corresponding values.

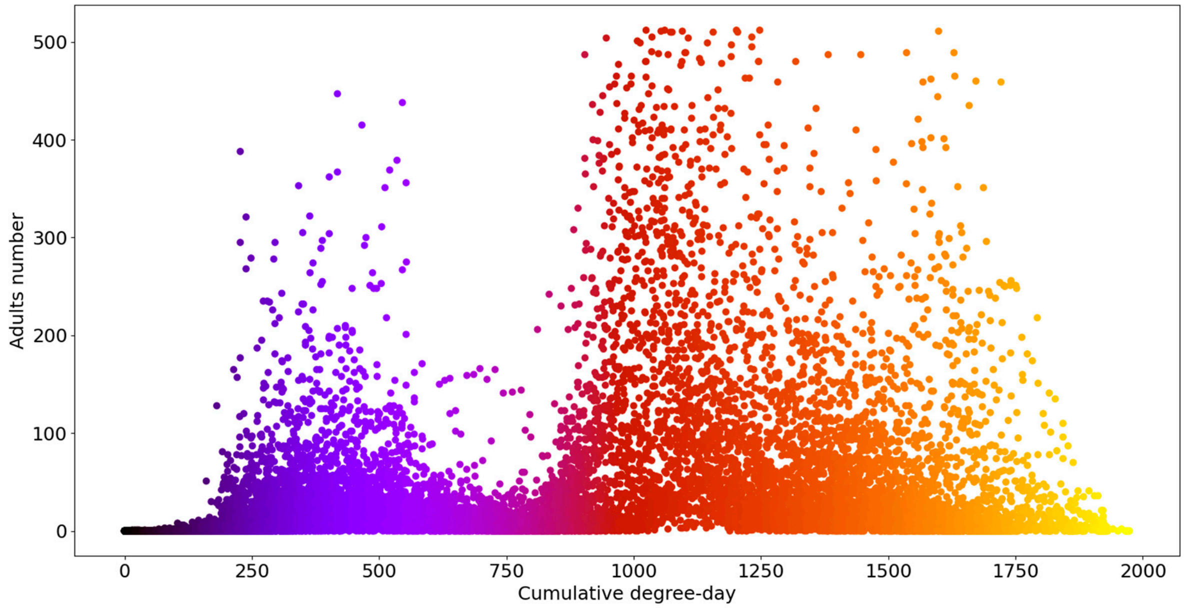

Figure 6. A scatter plot of the cumulative degree-days and the number of adults. The colour gradient is used only for the purpose of visualising the heat accumulation.

Furthermore, the calendar was used to predict the daily number of adults in the year 2021, and RMSE value of 46.67 was obtained, with daily values mainly being lower than calendar values (Figure 7). This implies that the annual profile for 2021 is below the calendar; hence, in that year a lower number of adults was recorded in the Vojvodina region when compared with the seven-year average. On the one hand, the calendar properly indicates the timing of the peak for all three generations in 2021, while on the other hand the error bars confirm the inter-annual variability presented in Figure 5. Inter-annual variability of the ECB population recorded by the light traps might depend on a crop structure in a particular year, i.e., the area covered by the corn fields and the distribution of the fields surrounding the traps in that year.

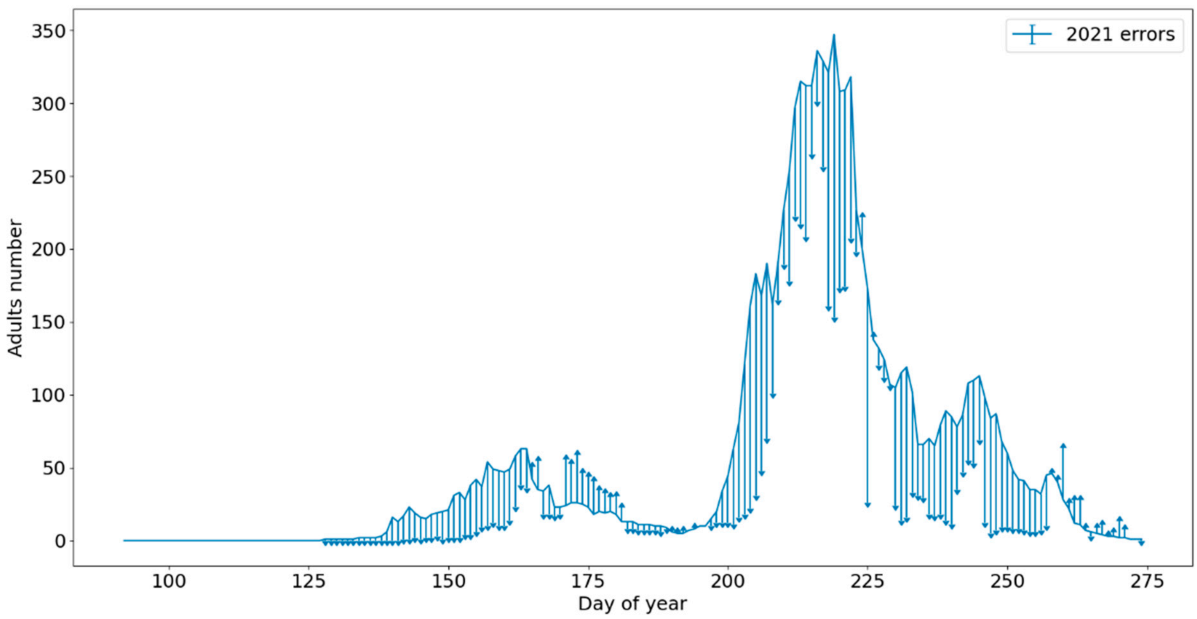

Figure 7. The prediction errors for 2021 obtained by using the calendar.

4. Discussion and Conclusions

According to a literature review, various mechanistic approaches have been used to model insect phenology, and several models have been applied to predict ECB flight [24,27,29,37–40]. The modelling mechanisms typically involve analysing the relationship between temperature, humidity, photoperiod, and other environmental factors and specific insect phenological stages [28].

The poikilothermic characteristic of insects (internal temperature varies with ambient temperature) has been used for a long time to develop phenological models based on degree-day accumulation [17,27,29,30]. The relationship between temperature and insect development is a concept that dates back to Charles Bonnet's investigation of the reproduction rate of *Aphis evonymi* Fabricius, 1775 (Hemiptera: Aphididae) [41]. Given the economic importance of the ECB, numerous authors have been involved in designing and testing degree-day accumulation models to define a physiological time scale that can be used to predict the development of the ECB. According to Got et al. [42], initial studies demonstrated the advantages [30] and limitations [43] of the degree-day model for describing and predicting ECB larval development. A degree-day model, which was developed and validated by Trnka et al. [27], is used to simulate the development and timing of the ECB. Temperature sums are used in conjunction with photoperiod and temperature stress thresholds to estimate the timing of the various ECB developmental stages [41]. Maiorano [24] compared two modelling solutions based on the same generic compartmental system. The first model was based on a nonlinear physiological relationship between temperature and development, with hourly temperatures used as input (HNL modelling solution). The second model was based on a linear relationship between temperature and degree-day accumulation using daily temperature (DL modelling solution). According to Maiorano [24], the use of a physiologically based response to temperature and hourly time steps may improve the accuracy of pest simulation models based on degree-day accumulation. Schaub et al. (2016) [40] parameterised a time-varying distributed delay model based on laboratory observations of the ECB developmental duration at constant temperatures. The model was run with hourly temperature records starting from January 1. According to the same author, the simulation model provides a valid and less labour-intensive alternative to observations for timing biological control in the corn-growing areas of Switzerland.

According to Got et al. [42], models based on a linear relationship between development rate and temperature are incapable of correctly describing development at temperatures outside the model's range of linearity. Got et al. [42] tested nine nonlinear models to describe the relationship between the development rate and temperature for the European corn borer. The same authors emphasised that temperature alone did not satisfactorily explain all of the variability under field conditions, regardless of which model was used to represent the relationship between development rate and temperature. Similar conclusions can be drawn from the results obtained in our study, as shown in Figure 6, where the number of adults detected by traps varies significantly for the same value of cumulative degree-days; for example, 1000 °C day^{-1} accumulated from the beginning of April can result in a low, medium, or high number of adults.

In our study, a phenological model was developed to calculate the daily number of adults by using nonlinear machine learning techniques and including relative humidity and precipitation in addition to cumulative degree-day, but its predictive power was low ($R^2 = 0.41$). On the other hand, models for predicting the timing of insect activity in a specific area can be a valuable tool for pest management, crop management, and conservation efforts. In terms of pest management strategies, such models can be extremely useful in identifying the best 'application window' for chemical or biological treatments and scheduling scouting activities in the field [24,44]. Choosing the best time window for chemical treatment in agriculture requires knowledge of the pests or diseases being targeted, the timing of their life cycle, and the efficacy of the agents being used. The timing of chemical or biological treatments in agriculture is a crucial factor that can significantly impact the effectiveness and efficiency of these treatments [19]. Considering the importance of defining the best time window for chemical treatment or biocontrol, predictive models can significantly increase the effectiveness of applied agents while minimising their negative impact on the environment and human health. As a result, our study calculated the calendar of the ECB in the Vojvodina region. Due to the high variability in the number of adults, the calendar was converted into the probability of ECB occurrence during the growing season.

According to our results, the probability of ECB occurrence obtained from the seven-year monitoring analysis indicates that the adult peak of the first, second, and third generation of ECB occurs in specific periods of the year (Figures 3 and 4). Figure 4 shows that the peak of the first generation of adults occurs at the beginning of June (160th–165th day of the year), the adult peak of the second generation can be expected at the beginning of August (215th–220th day of the year), and the peak of the third generation is most present at the end of August or early September (240th–245th day of the year). The predictive calendar was validated using the results of the 2021 monitoring, where the predictions of the ECB's flight dynamics showed satisfactory results with RMSE = 46.67 (Figure 7). According to the literature [24] the egg hatching maximum of each generation can be expected in the days after the adult flight peak; hence, a predictive calendar narrows the time interval for field inspection and control measure interventions. This approach may be a very useful tool for IMP strategies, potentially reducing the number of treatments required per generation of pest as well as operational costs. In the era of digitalisation, predictive models can be very easily integrated into existing digital platforms to alert farmers to critical periods of the year specific to certain crops and pests.

Predictive models are becoming increasingly important in agriculture due to the potential benefits they offer in terms of improving crop yields, reducing resource use, and increasing profitability. Such models can be used to track crop growth and development over time, allowing producers to identify patterns and trends that can assist them in making more informed decisions about crop management. Predictive models can be used to detect the early onset of pests and diseases in crops, allowing farmers to take action before the problem worsens. This can help to reduce crop losses and the need for expensive and potentially harmful pesticides [24,27,29,38–40]. The proposed calendar is rather static since it does not have the capacity to take into account the impact of changes in the weather variables that could occur in future. In coming years, development of the predictive models could involve more time series of observations, and hence the usage of sophisticated deep learning algorithms such as recurrent neural networks, along with the engineering of the meteorological features. Future research could include the analysis of crop classification maps for different years in Vojvodina, investigating the relationship between the area under corn fields inside the circular buffer with a 30 km radius surrounding the trap (as is standard in aerobiology) and the integral of the number of adults for that location.

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Data Availability Statement: Data collected by monitoring of the ECB are the property of the Forecasting and Reporting Service for Plant Protection of Serbia while the weather data are available at their official website.

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