



Phenological plasticity of *Cydalima perspectalis* and an assessment of the effectiveness of biological control methods in urbanised ecosystems

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Abstract. This study was conducted to develop an effective system for protecting boxwood against the invasive pest *Cydalima perspectalis* in the urban ecosystems of Ukraine. The work was based on field observations and laboratory analyses conducted in 2022-2023 at the Botanical Garden of the National University of Life and Environmental Sciences of Ukraine, the M.M. Hryshko National Botanical Garden of the National Academy of Sciences of Ukraine, the O.V. Fomin Botanical Garden, as well as in urban green spaces of Kyiv, including the Holosiivskyi National Nature Park and city squares. It was established that under the conditions of Kyiv, the pest forms two complete generations per season and a third generation of caterpillars that enter diapause and overwinter. Pheromone monitoring revealed two peaks of adult flight: in the first ten-day period of July and the first-second ten-day periods of August.

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A strong statistically significant inverse (negative) relationship ($R^2 = 0.96$) was identified between the daily temperature and the duration of the caterpillar stage. Mild winters ensured the survival of more than 70% of overwintering caterpillars. The evaluation of control methods showed that a biopreparation based on *Bacillus thuringiensis* achieved an efficiency of $96 \pm 1.2\%$ against early instar caterpillars (L1-L3). In comparison, the introduction of *Trichogramma* ensured parasitism of $71.5 \pm 2.6\%$ of eggs. In contrast, mechanical methods were significantly less effective ($45.0 \pm 3.9\%$). Based on the obtained data, a phenologically grounded treatment calendar and differentiated protection schemes for botanical gardens and urban squares were developed, allowing the minimisation of environmental risks and economic costs. The results form the basis for practical recommendations aimed at preserving boxwood plantings and minimising the pest's impact on biodiversity in Ukraine

Keywords: green spaces; *Cydalima perspectalis*; defoliation; pheromone monitoring; *Bacillus thuringiensis*; environmental safety

INTRODUCTION

The box tree moth (*Cydalima perspectalis* Walker, 1859) is an invasive species of the family Crambidae that causes significant damage to boxwood plantings in botanical gardens, park areas, and other urbanised ecosystems. Its high rate of spread, aggressiveness, and the lack of sufficient natural enemies in its secondary range result in considerable ecological and economic impacts. A similar threat to green spaces in Ukraine is posed by other invasive phytophagous insects, in particular the horse-chestnut leaf miner (*Cameraria ohridella* Deschka & Dimic, 1986) and the emerald ash borer (*Agrilus planipennis* Fairmaire, 1888), which indicates a general trend of the increasing role of invasive insects in the transformation of urbanised ecosystems (Puzrina et al., 2025). Studies on the phenology of *C. perspectalis* in various European regions reveal a high degree of plasticity in its life cycle. In most regions, two complete generations are formed, with the possibility of developing a third facultative generation under favourable temperature conditions. The mechanisms of diapause induction and regulation were studied by L. Poitou et al. (2020), while entomological monitoring in urbanised environments has shown that the spatial arrangement of plantings and the microclimate of the urban environment significantly influence the seasonal population dynamics (Marchenko, 2022).

The temperature regime is a key factor determining the rate of development and the number of generations of the species. R. Stan & I. Mitrea (2021) established a significant influence of temperature fluctuations on the duration of individual developmental stages and the overall

population dynamics. An increase in mean daily temperatures contributes to a reduction in the duration of the caterpillar stage and an increase in the invasive potential. Thus, climate change may enhance the risks of the pest spreading into new regions. Among modern approaches to regulating the abundance of *C. perspectalis*, priority is given to environmentally safe methods. The effectiveness of biopreparations based on *Bacillus thuringiensis* has been confirmed by a number of studies, including the work of Y.V. Koshelyaeva et al. (2024). Biotechnical measures, including pheromone monitoring and trapping, have been considered cost-effective tools for early population suppression in the study by K. Ok et al. (2023). In North America, emphasis is placed on the importance of early detection and an integrated approach to managing populations of the box tree moth (Coyle et al., 2022). Most studies confirm the potential of combining biological and other control methods.

Modelling population dynamics and spatial spread is an important tool for predicting invasions. Q. Canelles Trabal (2021) integrated population outbreaks into landscape modelling, which made it possible to assess potential risks to forest ecosystems. Using remote sensing, R. Esmaili et al. (2020) carried out mapping of plantings affected by the moth, facilitating a rapid response to the invasion. An assessment of the potential distribution of the species in Europe was conducted by Q. Canelles Trabal et al. (2021), confirming the dependence of its range on climatic parameters. Modern molecular genetic studies also expand understanding of the adaptive potential of *C. perspectalis*. An analysis of the mitochondrial genome



carried out by Y. Gao *et al.* (2023) has clarified the phylogenetic relationships of the species within the family Crambidae and deepened understanding of its evolutionary history.

Despite the considerable research conducted in Europe, data on phenological dynamics and the effectiveness of control methods against *C. perspectalis* in urbanised ecosystems of Ukraine remain limited. In particular, the influence of urban microclimatic conditions on the development of populations of this pest and the effectiveness of integrated pest management methods are still insufficiently studied. This study aimed to assess the phenological characteristics of the development of *C. perspectalis* under the conditions of the city of Kyiv and to analyse the effectiveness of different pest control methods. The objectives of the study included determining the seasonal dynamics of the development of the box tree moth and examining the influence of climatic factors on the rate of pest development. It also involved comparing the effectiveness of biological control methods, such as the use of *Bacillus thuringiensis* (Berliner, 1915) and entomophages, with mechanical methods at different stages of pest development.

MATERIALS AND METHODS

The study was conducted during 2022–2023 within the city of Kyiv (Ukraine). Observations and experiments were carried out at several representative sites: the Botanical Garden of the National University of Life and Environmental Sciences of Ukraine, the M.M. Hryshko National Botanical Garden of the National Academy of Sciences of Ukraine, the O.V. Fomin Botanical Garden, as well as in green spaces of the urban environment, including the Holosiivskyi National Nature Park and five urban squares located in four administrative districts of Kyiv: Shevchenkivskyi, Podilskyi (two squares), Pecherskyi, and Desnianskyi. Site selection was based not only on the age of plantings (≥ 10 years) and the presence of damage, but also taking into account location type (botanical garden/urban square/private plot), insolation (full sun/partial shade), density and varietal composition of the genus *Buxus* (at least 30 shrubs per site with an area of ≥ 50 m²), maintenance history (pruning, fertilisation, irrigation) and the use of insecticides/biopreparations over the previous 12 months, microclimatic conditions (mean daily temperature,

minimum winter temperatures, wind regime), soil and hydrological conditions (pH, drainage), the presence of nearby alternative habitats and sources of infestation (boxwood within a 200 m radius), as well as logistical factors (accessibility for monitoring, the possibility of establishing control subplots, and a minimum distance between sites of ≥ 200 m to minimise mutual influence).

The objects of the study were populations of *C. perspectalis* and the degree of damage inflicted on plantings of common box (*Buxus sempervirens* L.). For detailed analysis, 50 model plants were selected at each experimental site using a systematic sampling method, totalling 450 plants. The inclusion criterion was the presence of signs of moth damage in the previous season or location within an active infestation focus. The exclusion criteria were as follows: sites were not included in the study if at least one of the following conditions was present – recent treatments (contact insecticides within ≤ 30 days; systemic insecticides ≤ 60 days; biopreparations based on *Bacillus thuringiensis* or entomopathogenic fungi ≤ 10 days; releases of *Trichogramma* spp. ≤ 21 days); factors distorting damage assessment (intensive sanitary pruning within ≤ 14 days prior to the start; abiotic damage – frost, drought, or mechanical – with defoliation $> 25\%$; pronounced associated diseases of boxwood, such as box blight (*Calonectria pseudonaviculata*) exceeding level 2 on the damage scale); insufficient representativeness (< 30 *Buxus* shrubs per site, area < 50 m², inability to establish control subplots, distance to another experimental site < 200 m); manageable risks and access limitations (absence of written permission from the managing authority, lack of regular access or security; risk of plant removal or relocation during the study; proximity to sources of chemical drift – active treatments on neighbouring sites within < 20 m); as well as legal or quarantine restrictions preventing field experiments or conflicting with the study design.

To study the phenology and seasonal dynamics of the pest, visual assessment and pheromone monitoring methods were used. At each experimental site, five Delta pheromone traps (manufacturer Biosystems, Spain) equipped with *C. perspectalis* dispensers were installed. The traps were inspected, and the number of captured adults was recorded at 7-day intervals. During each inspection, the trap was temporarily removed, captured



insects were counted and identified by species and sex using tweezers and a magnifying lens, and the results were recorded in a field log. After counting, the captured specimens were removed, adhesive inserts were replaced with new ones, and dispensers were renewed according to the manufacturer's instructions to maintain monitoring effectiveness. In parallel, regular visual inspections of plantings were conducted to record the developmental stages of the pest (eggs, caterpillars of different instars, pupae, and adults). To assess the intensity of defoliation, a five-point scale was developed and applied: 0 – no damage; 1 – up to 20% leaf damage; 2 – 21-40%; 3 – 41-60%; 4 – 61-100%. To evaluate the influence of climatic factors, air temperature and relative humidity were recorded daily using portable digital thermo-hygrometers TFA Dostmann (Germany) installed at each site. To assess the relationship between daily temperature and the duration of the caterpillar stage, correlation and regression analysis were applied. A scatter plot was constructed to verify the linearity of the relationship, and model assumptions were tested using residual normality tests and checks for homoscedasticity. For the linear model, regression coefficients (β), the coefficient of determination (R^2), and p-values were reported. Model performance was evaluated using the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), allowing selection of the most appropriate model.

The effectiveness of control methods was assessed under field experimental conditions with four replicates ($n=4$). A biological preparation based on *Bacillus thuringiensis* var. *kurstaki* (Lepidocide, BTU-Centre Ltd., Ukraine) was applied at a concentration of 0.7% using fine-droplet spraying with a Gloria backpack sprayer (Germany). The introduction of the entomophagous agent *Trichogramma* spp. (manufacturer Biozakhyst, Ukraine) was carried out during the period of mass egg-laying by the moth, at a rate of 3,000 individuals per 100 m².

The effectiveness of the methods was calculated after 7, 14, and 21 days using Abbott's formula (1):

$$E = \frac{n_2 - n_1}{n_2} \times 100\%, \quad (1)$$

where n_1 is the number of live caterpillars in the treated plot, and n_2 is the number of live caterpillars in the control plot.

The economic assessment was carried out from the perspective of the managing authority of the green space, with a time horizon of one season and a base price year of 2023 (euro exchange rate in 2023: 1 EUR = 42.175 UAH (MinFin, 2023), corresponding to the study period); accounting units were UAH per 100 shrubs per season. Direct costs were estimated based on expenditures for biopreparations (Bt), biological material (*Trichogramma* spp.), labour (standard hours for treatment/monitoring), consumables, and pheromone monitoring (traps and dispensers). Economic benefits were assessed in terms of avoided costs for shrub replacement and restoration works. To compare the effectiveness of control strategies, independent experimental plots were established at each of the five study locations. Each experimental strategy and control at each location was represented by four replicates ($n=4$). The size of one elementary plot was 25 m² (5 × 5 m) and included at least five boxwood shrubs with moderate or severe damage.

The experimental groups included: Strategy 1 – treatment of phytophagous caterpillars with a biopreparation based on *Bacillus thuringiensis* (Bt). Strategy 2 (mechanical) – exclusive use of weekly mechanical inspections with removal of caterpillars. Strategy 3 – two releases of the entomophagous agent *Trichogramma* spp. followed by regular mechanical inspections. Control – plots without any intervention, only monitoring. Interventions were carried out synchronously across all locations at the recommended phenological periods. Effectiveness was assessed by visually counting live caterpillars on five fixed boxwood shrubs within each plot before the start of the experiment (baseline population) and after 7, 14, and 21 days. Data from individual replicates within each strategy at a given location were averaged for further analysis. Effectiveness at each assessment time was calculated using Abbott's formula (1) by comparison with the control group at the corresponding location.

To determine the sensitivity of different caterpillar instar groups to the *Bacillus thuringiensis*-based biopreparation, a separate experiment was conducted. *C. perspectalis* caterpillars were collected from natural populations and classified into instars based on morphological characteristics (head capsule width, body length) according to a standard scale: L1-L3 – early instars (1st, 2nd, 3rd



instars; body length < 10 mm); L4-L5 – late instars (4th, 5th instars; body length 10-20 mm). For each instar group (L1-L3 and L4-L5), four groups (replicates) of 20 individuals each were formed. Caterpillars were maintained on cut boxwood shoots in rearing cages under controlled conditions ($t = 23 \pm 2^\circ\text{C}$). Treatment was performed by spraying the plant surface with the recommended working concentration of the biopreparation. In control groups, shoots were sprayed with clean water. Caterpillar mortality was recorded 3, 5, and 7 days after treatment. Effectiveness for each instar group was calculated using Abbott's formula (1) on day 7 and expressed as the mean value of four replicates.

The economic analysis of control methods was carried out by comparing the costs of each method and assessing the total costs for each strategy per unit area. The calculations included expenses for biopreparations (Bt), *Trichogramma*, tools for mechanical collection, and labour costs. All costs were calculated for an area of 100 shrubs (50 m²). In addition, savings associated with avoiding the replacement of damaged plants and maintenance of green spaces were estimated, depending on the effectiveness of each control method. To assess the robustness of the economic conclusions, a sensitivity analysis was conducted with respect to fluctuations in the price of biopreparations ($\pm 20\%$) and changes in temperature conditions ($\pm 2^\circ\text{C}$). Based on these calculations, total costs for each strategy were determined, allowing comparison with potential benefits for the managing authorities of green spaces.

Statistical data processing was performed using the software package Statistica 10.0 (StatSoft, USA). Linear regression analysis was used to establish the relationship between temperature and the duration of the caterpillar stage. The significance of differences between the effectiveness indicators of different control methods was assessed using Student's t-test at a significance level of $p < 0.05$. All studies were conducted in accordance with the principles of ethical botanical research.

The research was carried out in compliance with the principles of the Convention on Biological Diversity (1992). All methods of controlling *C. perspectalis* populations were coordinated with the administrations of the botanical gardens and complied with the requirements of the Law of Ukraine No. 180-XIV "On Plant Protection" (1998).

The application of biological preparations and entomophagous agents was conducted in accordance with the principles of integrated pest management and minimisation of impacts on non-target insect species. No additional permits were required for researching invertebrates, as the box tree moth is an invasive pest, and the research methods were non-invasive or involved only the use of registered plant protection products.

RESULTS AND DISCUSSION

As a result of the conducted studies, it was established that during the growing season, *C. perspectalis* forms two complete generations. At the end of the season, a third generation of caterpillars develops, which enters diapause for the winter period. Overwintering occurs in dense white silken cocoons located between boxwood leaves deep within the shrub, protecting from unfavourable abiotic factors. The age structure of the overwintering population is represented predominantly by third-fourth instar individuals. The lower temperature threshold for caterpillar development is approximately $+10^\circ\text{C}$, which determines the onset of post-winter activity. In spring, overwintered caterpillars resume feeding. It was found that the timing of caterpillar hatching and mass adult flight varies depending on the climatic conditions of the given year. Figure 1 illustrates the phenological calendar of pest development for each generation based on observations in the city of Kyiv.

Despite nearly two decades of invasion in Central Europe, the biology of this species remains a subject of active scientific research. Earlier, S. Nacambo *et al.* (2014) reported that in Europe, the box tree moth may develop one or two generations per year. However, in connection with climate change, recent observations indicate the possibility of forming three to four complete generations per year, depending on local climatic conditions. The results of their own studies on the development of *C. perspectalis* in the city of Kyiv are consistent with the data presented in the work of O.Yu. Andrieieva *et al.* (2024) for the city of Zhytomyr. According to P.K. Bereś *et al.* (2021), who studied the invasion of the box tree moth in Poland, this pest forms two complete generations and one facultative generation. In Ukraine, as in Poland, the number of generations and their timing may vary depending on the temperature

and humidity conditions of a given year, which confirms the ecological plasticity of the species in response to climate change. To assess the relationship between daily temperature and the duration of the caterpillar stage, regression analysis

was applied. The results of the analysis are presented in Table 1, which includes the regression coefficient for temperature, the coefficient of determination (R^2), and the p-value for testing statistical significance.

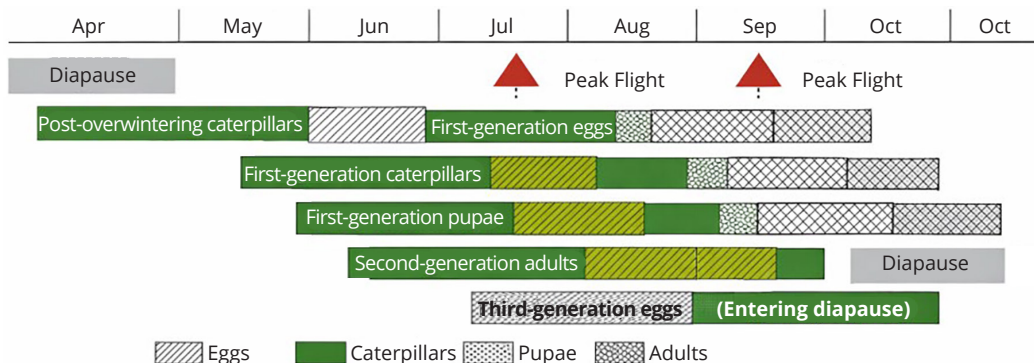


Figure 1. Phenological calendar of the development of *C. perspectalis* in the city of Kyiv

Source: developed by the authors based on their own research

Table 1. Results of correlation and regression analysis between temperature and the duration of the caterpillar stage of *C. perspectalis*

Parameter	Value	95% CI	p-value
β (temperature)	-0.28	[-0.35, -0.21]	<0.001
R^2	0.96		

Source: compiled by the authors based on their own research

The study revealed statistically significant differences in the rate of development of the box tree moth in sites with varying levels of isolation and wind protection. In urban squares with better solar exposure and higher mean daily temperatures, the development of the first generation of the pest occurred 5-7 days faster compared with more shaded and sheltered park areas, including the Holosiivskyi National Nature Park. This was

reflected in earlier hatching of *C. perspectalis* caterpillars and a reduced duration of transition to subsequent developmental stages in open, sunlit sites. In June-July, air temperatures in such areas were on average 2-3°C higher, creating favourable conditions for accelerated ontogeny and increased reproductive activity of the pest. Figure 2 shows the relationship between daily temperature and the duration of the caterpillar stage.

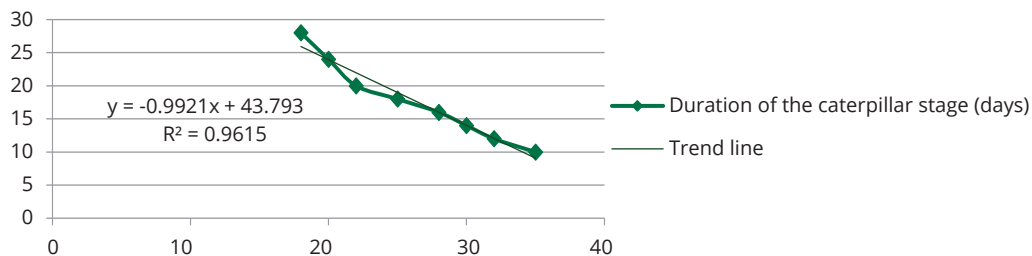


Figure 2. Scatter plot of temperature and the duration of the caterpillar stage of *C. perspectalis*

Source: compiled by the authors based on their own research

With an increase in mean daily temperature, the duration of the caterpillar stage decreases. The regression line clearly demonstrates an inverse correlation between temperature and stage duration, confirming that higher temperatures accelerate caterpillar development. This relationship shows some variation, particularly at extreme temperature values, which may indicate the influence of other factors such as humidity or specific microclimatic conditions. Comparison of information criteria showed that the linear model including only temperature (AIC = 145.2, BIC = 150.1) had an advantage over the quadratic model (AIC = 147.8, BIC = 154.5) and the model including humidity as a covariate (AIC = 146.5, BIC = 153.2), confirming its adequacy and sufficiency for describing the data.

The analysis demonstrated an “inverse (negative)” relationship between daily temperature and the duration of the caterpillar stage. Regression analysis revealed a correlation ($r < -0.80$), confirming a significant influence of temperature on developmental duration. For example, at a mean daily temperature of +25°C, the duration of the caterpillar stage decreased by 20% compared with conditions at +18°C. This indicates that increasing temperature accelerates the development process of caterpillars, reducing the time spent at each developmental stage. Table 2 presents the results of the comparison of caterpillar stage duration at different temperatures.

The study showed that mild winters with minimum temperatures not lower than -15°C ensure

high survival of overwintering *C. perspectalis* caterpillars. Under such conditions, their survival rate exceeded 70%, creating favourable conditions for the formation of high population densities in spring. In contrast, in years with more severe winters, when minimum temperatures dropped to -20°C, the survival of overwintering stages decreased significantly, resulting in lower numbers of caterpillars after the resumption of feeding. The obtained results confirm that temperature is a key factor determining the seasonal development of the box tree moth. Similar conclusions were reported by A. Wiesner *et al.* (2021), who found that temperature fluctuations significantly affect the phenology and population dynamics of this pest. Comparable patterns were also recorded in studies conducted in Kyiv. Furthermore, research by D. Schmera & B. Baur (2025) in Switzerland showed that increasing temperature shortens the duration of individual life cycle phases, thereby accelerating species development. Thus, the temperature regime determines not only winter survival but also the rate of generational development and the potential population size, which in turn influences the invasive potential of the species. Modelling of the potential distribution of *C. perspectalis*, carried out by M. Seehausen *et al.* (2024), confirms that climate change may contribute to the expansion of the pest's range. The consistency of local results with international studies indicates general patterns in the influence of climatic factors on the population dynamics of this invasive species.

Table 2. Duration of the *C. perspectalis* caterpillar stage at different temperatures

Temperature (°C)	Duration of the caterpillar stage (days)
18	28
20	24
22	20
25	18

Source: compiled by the authors based on their own research

Increased humidity during rainy periods promoted the development of fungal diseases among early instar caterpillars. Under conditions of cooling and high humidity, a significant spread of epizootics was observed, which reduced population density. These diseases had the greatest impact

on early instars (L1-L3), which were generally the most susceptible to such infections. During periods of elevated humidity and low temperatures, a reduction in population size of 15-20% was observed, significantly decreasing the overall impact of the moth on plants (Table 3).

Table 3. Effect of humidity and temperature on mycoses of *C. perspectalis*

Temperature (°C)	Humidity (%)	Reduction in population density (%)
18	85	18
20	75	15

Table 3. Continued

Temperature (°C)	Humidity (%)	Reduction in population density (%)
22	70	10
25	60	5

Source: compiled by the authors based on their own research

Thus, temperature conditions have a significant influence on the rate of development of box tree moth caterpillars, which in turn affects population dynamics throughout the season. Mild winters promote high survival of the overwintering stage, ensuring substantial population development during the growing season. In addition, increased humidity and prolonged rainy periods can significantly reduce population density due to the spread of diseases among caterpillars. These factors are important for predicting population development of the box tree moth and for managing its abundance in ecosystems.

The application of a bioinsecticide based on *Bacillus thuringiensis* var. *kurstaki* demonstrated high effectiveness against early instar caterpillars

(L1-L3), with a mortality rate of $96 \pm 1.2\%$. This indicates a high sensitivity of early larval stages to the preparation. At the same time, against later instars (L4-L5), effectiveness decreased to $65.3 \pm 2.5\%$, indicating their lower susceptibility to the bioinsecticide. The mechanism of action of the bioinsecticide lies in the formation of crystalline protein inclusions during bacterial sporulation. In the alkaline environment of the caterpillar gut, these inclusions dissolve, releasing insecticidal toxins (Malinowski, 2000). The obtained results confirm the advisability of early application of the preparation, as treatment at the initial stages of development ensures a substantial reduction in pest population density (Table 4).

Table 4. Effectiveness of a biopreparation based on *Bacillus thuringiensis* var. *kurstaki* against different instar groups of *C. perspectalis* caterpillars ($M \pm SD$; $n = 4$)

Caterpillar instar group	Effectiveness (%)
L1-L3	96 ± 1.2
L4-L5	65.3 ± 2.5

Note: effectiveness for each age group was calculated using formula (1) on day 7 and expressed as the mean of four replicates

Source: compiled by the authors based on their own research

The introduction of parasitoid wasps of the genus *Trichogramma* during the egg-laying period of the box tree moth in the Botanical Garden of the National University of Life and Environmental Sciences of Ukraine resulted in the parasitism of $71.5 \pm 2.6\%$ of moth eggs, which contributed to a significant reduction in the density of leaf-feeding caterpillars. This indicates the high effectiveness of *Trichogramma* as a biological control agent under botanical garden conditions. The results showed that the introduction of *Trichogramma* spp. is an effective method for controlling the abundance of the box tree moth, as it significantly reduces population size at the egg stage, thereby limiting subsequent caterpillar development. A comparative analysis of different control methods for the box tree moth revealed substantial differences in their effectiveness (Table 5). The

highest effectiveness was demonstrated by the application of a biopreparation based on *Bacillus thuringiensis* var. *kurstaki* – $95.0 \pm 1.4\%$. This high efficacy is due to the specific mode of action of the preparation, which targets larval stages of the pest and does not harm non-target organisms, thereby ensuring its environmental safety. The introduction of parasitic wasps of the genus *Trichogramma* achieved an effectiveness of $71.5 \pm 2.6\%$. This method targets the destruction of pest eggs and allows population control before caterpillars emerge; however, its effectiveness depends on the timing of release of the entomophagous agent and the population density of the phytophagous pest. The least effective method was mechanical control ($45.0 \pm 3.9\%$), which involves shaking and manual collection of caterpillars. The limited effectiveness of this approach is explained by

the ability of caterpillars to hide within dense foliage and silken shelters, as well as the rapid

recovery of the population due to the presence of multiple generations during the season.

Table 5. Effectiveness of population control methods for *C. perspectalis* (M ± SD; n = 4)

Control method	Effectiveness (%)
Biopreparation (<i>Bacillus thuringiensis</i> var. <i>kurstaki</i>)	95.0 ± 1.4
Introduction of <i>Trichogramma</i> spp.	71.5 ± 2.6
Mechanical destruction of caterpillars	45.0 ± 3.9

Note: efficiency was calculated using the formula (1)

Source: compiled by the authors based on their own research

Thus, the findings of this study are consistent with the results of N.V. Makarenko *et al.* (2019) regarding the effectiveness of a biopreparation based on *Bacillus thuringiensis* var. *kurstaki*, particularly at the early stages of caterpillar development. The effectiveness of biological control is also confirmed by data from other authors. In particular, L.M. Bondareva *et al.* (2021) reported high efficiency of phytocomplexes against early instar caterpillars under the conditions of the O.V. Fomin Botanical Garden. The promise of biological methods is also confirmed in the work of R. Murillo *et al.* (2025), dedicated to the use of insect pathogens. M. Budziszewska & P.K. Bereś (2024) emphasise the importance of biological control methods for the box tree moth in Europe, particularly the use of introduced entomophagous agents such as *Trichogramma* spp. Their findings fully correspond with the results obtained in the city of Kyiv, where the introduction of *Trichogramma* spp. ensured a significant reduction in the population size of the box tree moth. M. Usta *et al.* (2025) investigated

the pathogenic effect of *Penicillium glabrum* on the box tree moth. This study opens new perspectives for the use of entomopathogens in the biological control of this phytophagous species, which may also be considered in future research in Ukraine to ensure sustainable management of box tree moth populations. In addition, a positive effect of pheromone monitoring on the accuracy of predicting periods of intensive adult flight has been observed in Ukraine, which is important for the timely application of control measures.

To assess boxwood damage in areas infested by *C. perspectalis*, a five-point scale of defoliation intensity was applied. According to the observations, during the peak population of the second generation, 80% of the studied sites exhibited defoliation at levels 3-4, indicating severe to complete loss of foliage in these areas. According to the scale, level 3 corresponded to partial defoliation (41-60% of leaves), while level 4 corresponded to complete defoliation (61-100% of leaves) (Table 6).

Table 6. Results of the assessment of boxwood damage across all experimental sites

Defoliation level	Description of damage	% of sites with this level of damage
0	No damage	0
1	Light damage (up to 20%)	5
2	Moderate damage (20-40%)	10
3	Severe damage (41-60%)	30
4	Complete defoliation (61-100%)	55

Source: compiled by the authors based on their own research

The least affected sites were observed in urban squares, where only 5% of areas showed light damage (level 1). This may be due to lower exposure to direct sunlight and more favourable conditions for boxwood growth, which reduce pest activity. The most severely affected sites were located in well-lit areas of botanical gardens, where

defoliation reached 61-100% on 55% of the sites. This is associated with higher levels of isolation, which created optimal conditions for the development of multiple generations of the box tree moth during the season. The maximum level of boxwood defoliation was observed in July-August, during the development of the second generation



of the box tree moth, when caterpillar abundance reached peak levels. This led to significant damage to green spaces and deterioration of their phytosanitary condition. Similar conclusions were reported by A.M. Hnatiuk & M.B. Haponenko (2016), who identified the box tree moth as one of the main threats to green spaces in Kyiv. The obtained results also indicate a negative impact of the pest on the biodiversity of the studied areas, which justifies the need for a comprehensive approach to regulating its population. A similar trend of rapid population growth and active spread of the species was recorded by A. O'Hanlon (2024) in Ireland, confirming the pan-European nature of the invasion and the relevance of timely control measures.

Based on the obtained phenological data, a treatment calendar was developed to optimise the timing of interventions aimed at reducing the abundance of *C. perspectalis* at different stages of its development. The first treatment is recommended in late April to early May, when overwintered caterpillars begin to hatch. This allows control of the pest at a stage when it is most susceptible to biological preparations such as *Bacillus thuringiensis*. The second treatment is scheduled for mid-July, when the peak abundance of L1-L3 caterpillars of the first generation is observed. The third treatment in mid-August significantly reduces population size before the onset of autumn, when the life cycle of most individuals is completed (Table 7).

Table 7. Timing of treatments and corresponding developmental stages of *C. perspectalis*

Generation	Approximate treatment period	Dominant caterpillar instar stages	Biological justification for the application	Purpose of treatment
Overwintered generation	Late April – early May	L3-L4	Resumption of feeding after emergence from diapause	Reduction of the overwintered population
First generation	Mid-July	L1-L3	Mass hatching of caterpillars and the onset of active feeding	Prevention of peak defoliation
Second generation	Mid-August	L1-L3	Onset of development of the second population wave	Limitation of population size before entering diapause

Note: dates may vary depending on the weather conditions in a given year

Source: compiled by the authors based on their own research

To ensure effective control of the box tree moth under different types of plantings, differentiated approaches were proposed. For botanical gardens, where the preservation of biodiversity and ecological balance is essential, priority is given to biological control methods, such as the use of entomophagous agents (e.g., *Trichogramma* spp.) and pheromone monitoring. This allows precise determination of periods of the most intensive adult flight and the timely implementation of population control measures without the use of chemical

treatments. In urban squares, where a higher level of urbanisation is often observed, and fewer opportunities exist for the implementation of biological methods, a combined approach is more appropriate. In this case, biopreparations based on *Bacillus thuringiensis* were used to control early instar caterpillars (L1-L3), together with mechanical control methods such as shaking caterpillars from foliage during peak population periods. These methods made it possible to reduce population density while minimising environmental impact (Table 8).

Table 8. Approaches to the protection of boxwood from *C. perspectalis* depending on the type of plantings

Type of plantings	Main control methods	Additional measures
Botanical gardens	Biological methods (<i>Trichogramma</i> spp.), pheromone monitoring	Forecasting the timing of treatments
Urban squares	Biopreparations (<i>Bacillus thuringiensis</i>), mechanical control	Shaking off caterpillars, timely treatments

Source: compiled by the authors based on their own research



The proposed approaches to protecting plantings from *C. perspectalis* are based on the results of their own phenological observations and take into account the specific characteristics of different types of green spaces. Differentiation of methods depending on the level of urbanisation and the ecological value of plantings makes it possible to optimise control effectiveness and minimise negative environmental impacts. The appropriateness of applying integrated and biologically oriented approaches is also confirmed by the results of international studies. In particular, A.R. Armanda & M. Bjeliš (2025), in their review of the box tree moth invasion in Europe, emphasise the need to combine biological and mechanical population management methods. Similar conclusions have been drawn in Ukrainian studies, where the combination of biopreparations with mechanical control increases overall effectiveness while reducing environmental pressure. Further research indicates that in Europe, *C. perspectalis* lacks sufficiently effective natural enemies capable of significantly limiting its abundance (Budziszewska & Bereś, 2024), which necessitates the systematic application of integrated methods throughout the growing season, especially given the overlap of generations. In addition, modern approaches to pest population management are increasingly based on predictive distribution models. M. Kenis (2022) and Ş. Yaman & M. Yaman (2024) demonstrated the effectiveness of using spatial distribution models to assess invasion risks. The obtained forecasts can be adapted to the conditions of Ukraine, taking into account climate change, which contributes to the expansion of the species' range.

The economic justification of a comprehensive approach to controlling *C. perspectalis* populations, taking into account the market cost of labour (100 UAH/hour; EUR 1=UAH 42.175), confirmed the feasibility of combining biological and mechanical methods, while also demonstrating a significant increase in the share of labour costs within the overall cost structure. The use of biopreparations at early stages of pest development contributes to a substantial reduction in population size, potentially decreasing the need for intensive mechanical measures and chemical treatments. The economic efficiency of control methods was assessed by comparing direct costs for each measure and determining total costs per unit area. Direct costs

included the price of biopreparations, labour, and expenses for materials and tools used in mechanical control. The cost of the biopreparation *Bacillus thuringiensis* var. *kurstaki* was UAH 500 (EUR 11.86) per litre, sufficient to treat 1,000 m². For an area of 100 shrubs (approximately 50 m²), the cost of the preparation amounted to UAH 25 (EUR 0.59), while labour costs for a 2-hour treatment were UAH 200 (EUR 4.74). The total cost of applying the biopreparation was therefore UAH 225 (EUR 5.33) per 100 shrubs. The introduction of *Trichogramma* spp. cost UAH 150 (EUR 3.56) per 1,000 individuals (per 100 m²); for 50 m², the cost of biological material was UAH 75 (EUR 1.78). Including labour costs (approximately 1.33 hours, or UAH 133 – EUR 3.15), the total amounted to UAH 208 (EUR 4.93) per 100 shrubs. Mechanical control through shaking and manual collection of caterpillars required approximately 2.67 hours of work, resulting in labour costs of UAH 267 (EUR 6.33) per 100 shrubs. The total cost of the combined approach (biopreparation + *Trichogramma* spp. + mechanical control) was UAH 700 (EUR 16.60) per 100 shrubs. The results indicate that under current economic conditions, labour costs are the determining factor in the overall cost structure, with mechanical methods representing the most expensive component of the control system.

To assess the impact of changes in control method costs, a sensitivity analysis was conducted regarding fluctuations in the price of biopreparations and changes in temperature conditions. The modelling results showed that a 20% increase in the cost of *Bacillus thuringiensis* leads to an increase in total costs by UAH 6-7 (EUR 0.14-0.16) per 100 shrubs. Temperature changes of 2°C affect caterpillar development and, consequently, the effectiveness of biopreparations, potentially altering costs by 5-10% depending on the number of required treatments. Combined control methods for the box tree moth, including biopreparations and the introduction of *Trichogramma* spp., minimise environmental risks and plant losses, making these strategies optimal for long-term pest population management. Thus, the practical recommendations proposed in this study are consistent with contemporary international approaches to regulating *C. perspectalis* populations and take into account both local phenological characteristics and broader European trends in the spread of this pest.



CONCLUSIONS

As a result of the conducted study under the conditions of the city of Kyiv, comprehensive data on the bioecology of *C. perspectalis* were obtained, and elements of a system for protecting boxwood from this invasive pest were developed. It was established that in Kyiv, the pest forms two complete generations. At the end of the season, a third generation of caterpillars develops, which enters diapause for the winter period. The periods of mass hatching of early instar caterpillars are critical for population control. A statistically significant relationship between air temperature and the duration of caterpillar development was identified. An increase in mean daily temperature from 18°C to 25°C reduces the duration of the caterpillar stage by 20%, which significantly affects population dynamics. It was demonstrated that mild winters with minimum temperatures not lower than -15°C ensure the survival of more than 70% of overwintering stages, leading to intensified reproduction in the following year.

The evaluation of the effectiveness of different control methods showed the advantage of biological approaches. A biopreparation based on *Bacillus thuringiensis* demonstrated an effectiveness of $96 \pm 1.2\%$ against early instar caterpillars (L1-L3), whereas against later instars (L4-L5) this rate decreased to $65.3 \pm 2.5\%$. The introduction of *Trichogramma* spp. ensured parasitism of $71.5 \pm 2.6\%$ of eggs, which is a high level for biological control. Mechanical methods proved to be the least effective ($45.0 \pm 3.9\%$), but may be used as a supplementary

element of an integrated system. A differentiated approach to plant protection is proposed: for botanical gardens, priority is given to biological methods and pheromone monitoring, whereas for urban squares, a combination of biopreparations and mechanical control is recommended. The developed phenologically grounded treatment calendar allows optimisation of intervention timing and improvement of its effectiveness.

The limitations of the study include its regional scope and the two-year observation period, which did not allow for a full assessment of the impact of extreme weather conditions on pest populations. In addition, the research was conducted primarily in urbanised ecosystems, and therefore, the obtained results may differ from those under forest conditions. Prospects for further research include the study of the effectiveness of new biopreparations, monitoring of the duration of pest resistance, and investigation of the impact of the box tree moth on different varieties and forms of boxwood, which is of particular importance for the conservation of biodiversity in urban ecosystems of Ukraine.

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Фенологічна пластичність *Cydalima perspectalis* та оцінка ефективності біологічних методів контролю в умовах урбанізованих екосистем

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Анотація. Дослідження проведено з метою розробки ефективної системи захисту самшиту від інвазійного шкідника *Cydalima perspectalis* в умовах урбанізованих екосистем України. Робота ґрунтувалася на польових спостереженнях та лабораторному аналізі, проведених у 2022-2023 роках на території Ботанічного саду Національного університету біоресурсів і природокористування України, Національного ботанічного саду імені М. М. Гришка Національної академії наук України, Ботанічного саду імені академіка О. В. Фоміна, а також у зелених насадженнях м. Києва, зокрема в Національному природному парку «Голосіївський» та міських скверах. Встановлено, що в умовах м. Києва шкідник формує дві повні генерації за сезон і третє покоління гусені, що впадає у діапаузу і зимує. Феромонний моніторинг виявив два піки льоту імаго: у I декаді липня і I–II декадах серпня. Виявлено сильний статистично значущий зворотний (негативний) зв'язок ($R^2 = 0,96$) між середньодобовою температурою повітря та тривалістю стадії гусені. М'які зими забезпечували виживаність понад 70 % зимуючих гусениць. Оцінка ефективності методів контролю показала, що біопрепарат на основі *Bacillus thuringiensis* досягав ефективності $96 \pm 1,2$ % проти гусеней молодших вікових стадій (L1–L3), а інтродукція трихограми забезпечила паразитування $71,5 \pm 2,6$ % яєць. Натомість механічні методи були значно менш ефективними ($45,0 \pm 3,9$ %). На підставі отриманих даних розроблено фенологічно обґрунтований календар обробок та диференційовані схеми захисту для ботанічних садів і міських скверів, що дозволяють мінімізувати екологічні ризики та економічні витрати. Результати є основою для практичних рекомендацій щодо збереження самшитових насаджень та мінімізації впливу шкідника на біорізноманіття в Україні

Ключові слова: зелені насадження; *Cydalima perspectalis*; дефоліація; феромонний моніторинг; *Bacillus thuringiensis*; екологічна безпека