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The Invasive Box Tree Moth Five Years after Introduction in Slovakia: Damage Risk to Box Trees in Urban Habitats

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Abstract: The box tree moth *Cydalima perspectalis* (Walker, 1859) (Lepidoptera: Crambidae) is an invasive species in Europe and a serious pest of box trees (*Buxus* spp.). In Slovakia, Central Europe, it was first reported in 2012 within the low elevation region with a warm climate. We hypothesize that the cold mountain region of Slovakia would provide less suitable conditions for the spread of this species, indicated by no or only slight damage to box trees. Five years after *C. perspectalis* was first recorded in Slovakia, we assessed the probability of occurrence of the moth and the probability of damage to box trees (*Buxus sempervirens*) by its larvae, using temperature and altitude data as predictors. In June and July 2017, at 156 locations (towns and villages) between the altitudes of 109 and 888 m, we recorded damage and categorized the intensity of damage to box trees by *C. perspectalis* using a four-point scale. Box trees infested by *C. perspectalis* were recorded in most locations at altitudes between 110 and 400 m with the mean annual temperature varying between 10.5 and 7.9 °C. High damage to box trees was found in locations up to 340 m a.s.l. characterized by mean annual temperatures above 8.5 °C. Our results suggested high probability (>60%) of any damage to box trees for the area up to approximately 300 m a.s.l. (mean annual temperature above 8.4 °C), and high probability (>60%) of high damage for the area up to approximately 250 m a.s.l. (mean annual temperature above 9 °C). The area where damage to box trees was predicted using the altitude showed great overlap with the area predicted using the mean annual temperature. The area with the probability of any damage was only slightly larger than the area with the probability of high damage.

Keywords: urban trees; damage to trees; *Cydalima perspectalis*; insect pests; invasive species; non-native species; Central Europe

1. Introduction

The box tree moth *Cydalima perspectalis* (Walker, 1859) (Lepidoptera: Crambidae) is an invasive species native to eastern Asia [1]. In Europe it was first recorded in Germany in 2006 [2], from where it has quickly spread to many parts of the continent [3,4]. For example, it moved eastwards to Central

Europe and was found in Switzerland in 2007, Austria in 2009, Hungary in 2010, the Czech Republic in 2011, Slovakia and Poland in 2012 and the western part of Ukraine in 2016 [4–6].

Cydalima perspectalis has spread within Europe actively (spontaneously) as well as passively through the transport of infested host plants (*Buxus* spp.) [2,6–9]. The trade with ornamental plants is crucial for spread of harmful pests [10]. The transport of host plants resulted in the establishment of the moth far beyond the area of its previously known distribution, e.g., in Bucharest, Romania, in 2011 [11], southwestern Poland in 2012 [12], Istria, Croatia, in 2012 [13], Sicily, Italy, in 2013 [3], Sochi, the Russian Black Sea coast, in 2013 [14], and the Bulgarian Black Sea coast in 2014 [15]. Due to the movement of adult moths and anthropogenic activity, further spread from these locations continued [6,7,16–19]. Adult *C. perspectalis* can spread actively at the dispersal rate of approximately 10 km per year [2,20].

Slovakia, located in Central Europe, in the area of the expected occurrence of *C. perspectalis* [21], has rugged (diverse) topography (Pannonian Basin and Carpathian Mountains) and a variety of landscapes [22]. Climate conditions in the country (warm, moderately warm, and cool regions) correspond with the altitudinal range from 94 m to 2655 m a.s.l. [23]. Hence, this territory with such diverse climates provides ideal conditions to study the local spread of this invasive species. Box trees (*Buxus* spp.), the hosts of this invader, although non-native to Slovakia, are widespread and often grown there as ornamental plants in private and public gardens, parks, and cemeteries, *Buxus sempervirens* being the most popular box species.

Data on the spread of *C. perspectalis* within Europe indicate that the moth arrived in Slovakia from the southwest. It was recorded in Bratislava (48.1423717 N, 17.0991427 E) in south-west Slovakia in 2012 [24], very likely as a result of spread from nearby locations in Austria—occurrence since 2010 [4], Hungary—since 2011 [6,25], and the Czech Republic—since 2011 [26]. In the same year (2012), *C. perspectalis* was also recorded in another location in Slovakia—Turňa nad Bodvou, 285 km east of Bratislava (48,6004045 N, 20,8776599 E) (Panigaj, unpublished record). It is assumed that the moth was imported to this location with the box trees. The two distant locations are situated in a warm region of south Slovakia [23]. Over the following years, *C. perspectalis* infested the box trees in this region in many locations ([27]; our unpublished data). However, possible further spread of the moth to colder regions of the country was not reported.

The aim of our study was to investigate the spread of *C. perspectalis* in Slovakia from the warm areas at low altitudes to the colder areas at higher altitudes, over a six year period. Main emphasis was placed on relationships between damage to box trees and altitude, and between damage to box trees and temperature conditions in particular locations. Altitudinal and temperature data would be utilized by horticultural practices in predicting not only the spread of *C. perspectalis* but also the damage to box trees across the country as a novel research output. We hypothesized that the moth gradually spread to the colder regions of the West Carpathians, causing only slight or no damage to box trees. We expected that the colder climate would limit the occurrence and hamper the spread of *C. perspectalis* [21].

We focused on (1) the distribution of *C. perspectalis* and the degree of damage to box trees by this pest in the West Carpathians and the adjacent areas of the Pannonian Basin, and (2) the assessment of the probability of occurrence of *C. perspectalis* and the probability of the degree of damage to host plants by this species in relation to local temperatures and altitude five years after the introduction of the moth in Slovakia.

2. Materials and Methods

2.1. Data Recording

In June and July 2017, we inspected the damage to box trees by *C. perspectalis* in 156 locations in the Pannonian Basin and the West Carpathians from the western border of the Slovak Republic to the city of Košice in the east of the country (109 m–888 m a.s.l.) (Supplementary Materials, Table S1). Damage was always assessed by the same three people (experienced entomologists). The examined box trees (*Buxus sempervirens*) were planted as ornamental plants, mostly in cemeteries and less frequently in

town parks. In the years after the introduction of *C. perspectalis* in Slovakia (2012–2017), box trees were not treated or were treated with pesticides only rarely. This enabled us to obtain reliable data on the damage caused to box trees by the invasive moth. Box trees occur in most urban areas in the country, showing great variation in number. The number of trees in particular locations ranged between 1 and 163 (total number of trees = 2304, median = 8.0), and all of these trees were inspected. Only six locations had a single box tree.

We recorded damage to box trees by *C. perspectalis* visually in situ. Four levels of damage to box trees were used:

- No damage (no foliage damaged),
- Low damage (≤1/3 of foliage damaged),
- Medium damage (>1/3, ≤2/3 of foliage damaged), and
- High damage (>2/3 of foliage damaged, box trees appeared dry due to damage).

There were locations with certain trees undamaged, certain trees damaged slightly and certain trees damaged moderately or heavily. The level of damage was assessed for these locations according to trees with the highest level of damage recorded. This reflected the potential of *C. perspectalis* to cause damage to box trees in particular locations.

2.2. Statistical Analyses

Data on the occurrence of *C. perspectalis* in other Central European countries up to 2017 were extracted from various sources—Czech Republic [26,28–30]; Austria and Germany [4]; Hungary [5,31,32]; Ukraine [5]; and Poland [12,33,34]. For spatial data analysis the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) with pixel resolution of 30 m was adopted [35]. Data on the mean annual temperatures in the gridded form, with spatial resolution of 100 m, were obtained from the Climate Atlas of Slovak Republic [23]. These data (source: meteorological stations in Slovakia, 1961–2010) were derived by the interpolation of the long-term mean air temperature measured at 2 m above the ground. Since the temperature field is dependent on the altitude, the elevation map was taken into account in the interpolation. For the broader area of the Central European region, climate data in gridded form from WorldClim—Global Climate Data project, were chosen, with spatial resolution of 30 s (0.008°) [36]. From this data set the annual mean air temperature at 2 m height was selected, with the data representing the 30 year average over the period 1971–2000.

The mean air temperature in January and the mean number of days with frost were also examined. Due to a strong correlation between these variables and the mean annual temperature, only the latter was included in further analyses, since it provided the best results with regard to their interpretation.

Preprocessing of the statistical analyses was made using QGIS 2.18 software. It involved two steps. Firstly, a reprojection of original layers was made. For the purpose of Central European analyses, the layers were projected into the WGS84—UTM34N coordinate system (EPSG code 32634). The layers for Slovakia were projected into the national coordinate system S-JTSK Krovak (EPSG code 102067). Secondly, the information from the digital elevation model (DEM) and the climate data sets was extracted into the visited study locations using the Point Sampling Tool in QGIS.

A total of 156 locations (data points) were analysed. Each data point included information about damage to box trees in the order: 1—no damage, 2—low damage, 3—medium damage, or 4—high damage. Considering the ordinal scale of the dependent variable "damage" with four categories (levels), the ordinal logistic regression was applied (e.g., [37,38]). The digital elevation model (DEM) and the layers of annual mean air temperature field at the height of 2 m were used as independent (explanatory) variables in the regression model, providing the probabilities of (A) high damage, (B) high and medium damage, and (C) high, medium, and low damage to box trees (probability of any kind of damage). The probabilities were described by the logistic (sigmoid) curves, the formulae of which were used in the QGIS Raster Calculator tool to produce the final maps. Statistical analyses were performed in R (version 3.5.1) [39].

3. Results

Box trees damaged by *C. perspectalis* were found in 82 locations; high damage was recorded in 61 locations, medium damage in 6 locations, and low damage in 15 locations. In total 74 locations had only undamaged box trees.

The infestation of box trees by the pest was mostly (in more than 95% of the locations, $n = 82$) recorded at altitudes ranging from 110 m to 400 m where mean annual temperature varied between 10.5 °C and 7.9 °C.

Box trees with high damage mostly (in more than 95% of the locations, $n = 61$) occurred in areas up to 340 m a.s.l. where mean annual temperature was above 8.5 °C. The highest and coldest location with high damage was the cemetery in the village of Betliar (48.701414 N, 20.514649 E; 360 m a.s.l., mean annual temperature 8.0 °C).

Medium and low damage to box trees was mostly (in more than 75% of the locations, $n = 21$) recorded in areas between 200 m and 390 m a.s.l. where mean annual temperature was between 9.2 °C and 7.9 °C. Locations without infested box trees were also relatively frequent here. The highest and coldest location with damaged box trees (low damage) was the cemetery in the village of Štiavnické Bane (48.436295 N, 18.860747 E; 686 m a.s.l.; mean annual temperature 6.5 °C).

The collected data enabled us to predict the probability of damage to box trees by *C. perspectalis* in relation to the altitude and the mean annual temperature of the location (Figures 1 and 2). For example, the probability of any damage to box trees (high, medium, or low), and thus the probability of occurrence of this pest, was higher than 60% in the areas with altitudes up to approximately 300 m. The probability of high damage was higher than 60% in locations with altitudes up to approximately 250 m (Figure 1).

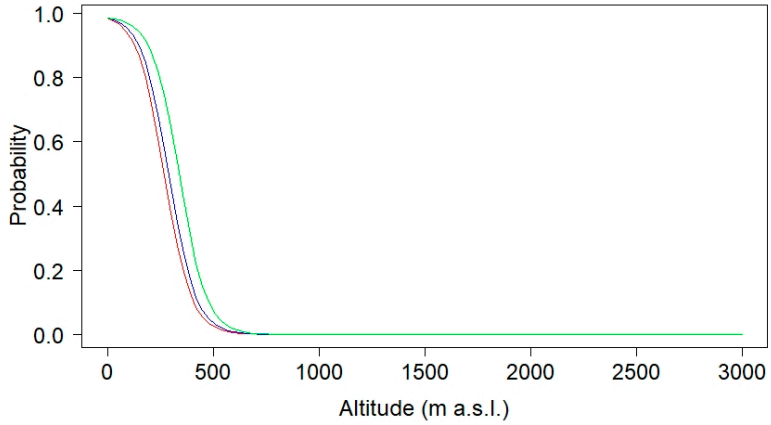

Figure 1. The probability of damage to box trees by *Cydalima perspectalis* predicted by altitude. Red line—high damage; blue line—high or medium damage; and green line—any damage (high, medium, or low damage).

In locations where the mean annual temperature was above approximately 8.4 °C, the probability of occurrence of damaged box trees was higher than 60%. In locations where the mean annual temperature was higher than approximately 9 °C, the probability of high damage was over 60% (Figure 2).

The range of altitudes and mean annual temperatures predicting the probability of high or medium damage was similar to that predicting the probability of high damage. The range of altitudes and mean annual temperatures predicting the probability of any damage (high or medium or low) was broader (Figures 1 and 2).

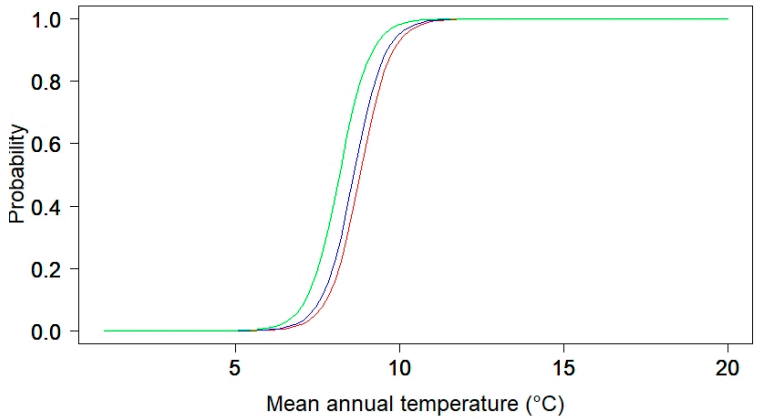

Figure 2. The probability of damage to box trees by *Cydalima perspectalis* predicted by mean annual temperature. Red line—high damage; blue line—high or medium damage; and green line—any damage (high, medium, or low damage).

The damage to box trees and the probability of high damage to box trees in relation to altitude and mean annual temperature in the locations in Slovakia and the surrounding regions are shown in Figures 3 and 4.

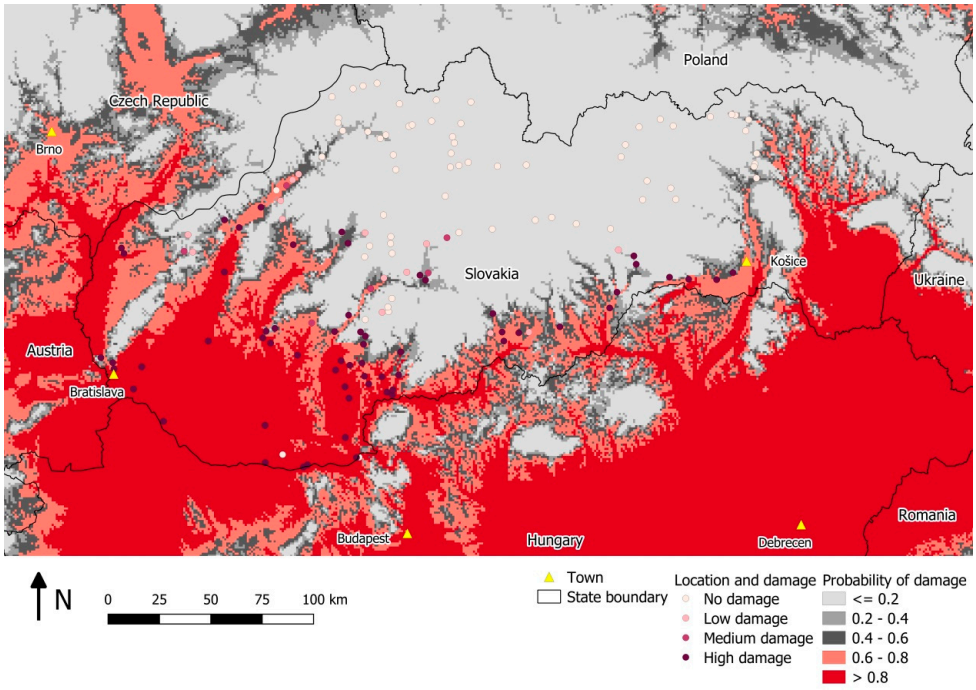

Figure 3. Map of Slovakia and surrounding regions showing the probability of high damage to box trees by *Cydalima perspectalis* predicted by altitude.

The probability of high damage was highest within the entire (compact) territory in the south-west and the east of Slovakia within the Pannonian Basin, in the southern parts of central Slovakia and the southern parts of the Carpathians valleys. The areas with the probability of high damage, predicted by altitude and mean annual temperature (correlated variables), showed great overlap. Small differences between these areas were found e.g., in the northern and colder parts of the valleys. High damage to box trees was also recorded in a few locations within the area with low probability of high damage. Nevertheless, all these locations were adjacent to the area where high damage was highly likely (Figures 3 and 4).

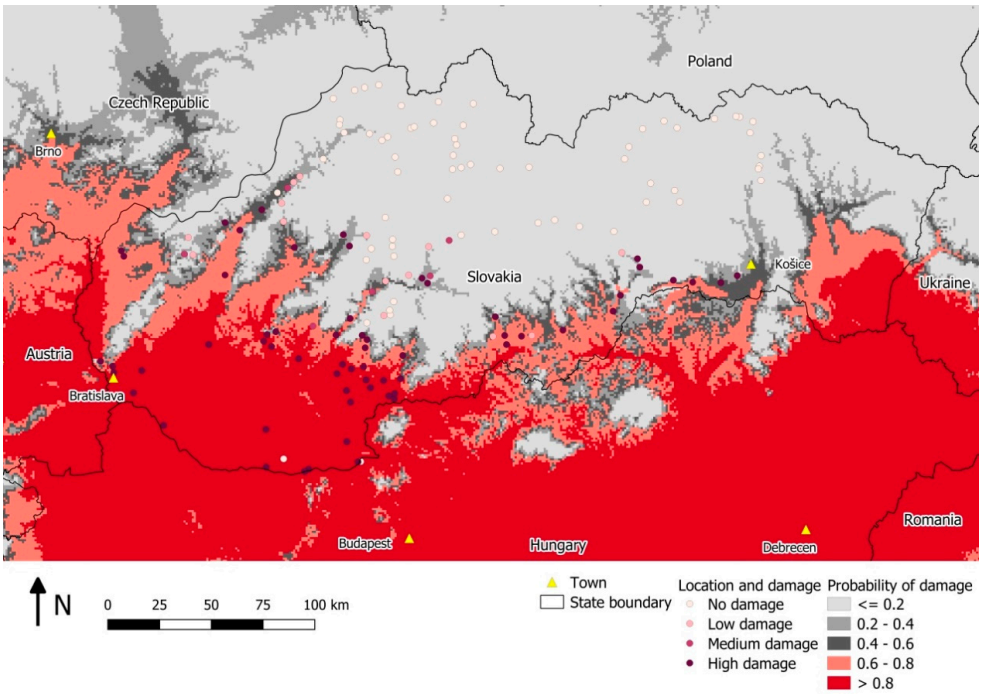

Figure 4. Map of Slovakia and surrounding regions showing the probability of high damage to box trees by *Cydalima perspectalis* predicted by mean annual temperature.

The probability of any kind of damage (high, medium, or low) to box trees by *C. perspectalis* in relation to altitude and mean annual temperature in Slovakia and in the surrounding regions is shown in Figures 5 and 6.

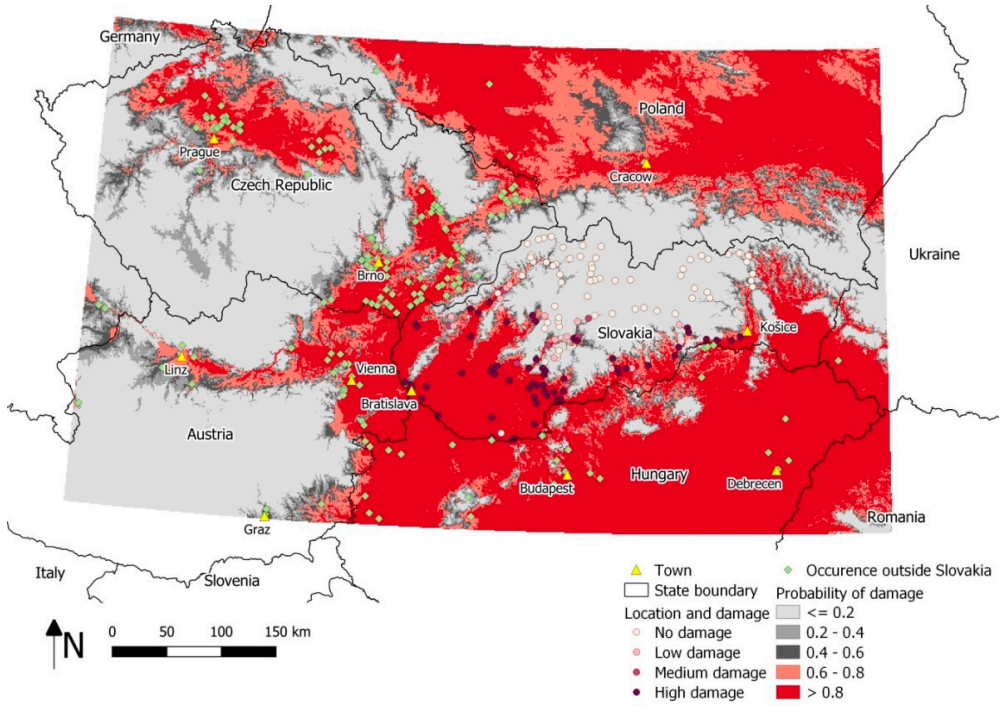

Figure 5. Map of Slovakia and surrounding regions showing the probability of any damage to box trees by *Cydalima perspectalis* predicted by altitude. Locations and damage to box trees in Slovakia—original (own) data; occurrence outside Slovakia—data from the literature.

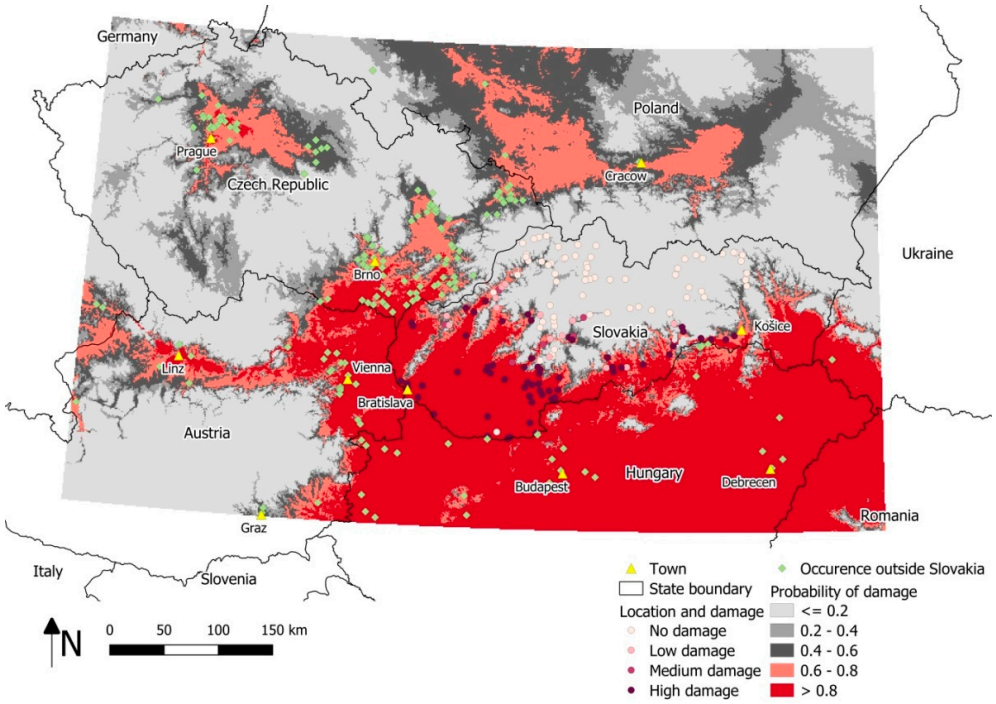

Figure 6. Map of Slovakia and surrounding regions showing the probability of damage to box trees by *Cydalima perspectalis* predicted by mean annual temperature. Locations and damage to box trees in Slovakia—original (own) data; occurrence outside Slovakia—data from the literature.

The probability of any kind of damage was calculated using our own data from Slovakia; the data on the occurrence of *C. perspectalis* in the neighboring countries by 2017 were compiled from various sources (see Materials and Methods). The area with the probability of any damage was only slightly larger than the area with the probability of high damage.

In Slovakia, the areas with damaged box trees, characterized by their altitude and mean annual temperature, showed a great overlap. A similar overlap can be seen in the examined parts of Austria, Hungary, and Ukraine. In the Czech Republic and Poland, the area with the probability of damage to box trees higher than 60%, estimated by the altitude, was larger than the area estimated by the mean annual temperature. Until 2017, *C. perspectalis* was recorded in the displayed areas of Austria and Hungary with high probability of damage (over 80%) estimated by either altitude or mean annual temperature. The occurrence of *C. perspectalis* in the Czech Republic until 2017 was recorded in the area with high probability of damage (higher than 80%) estimated by the altitude. However, the known occurrence of the moth in this country was connected with the area characterized by the lower probability of damage (60–80% or lower) estimated by the mean annual temperature. In the displayed parts of Poland, only a few records of *C. perspectalis* were available up to 2017; with most of them coming from the territory with expected damage to box trees (the probability of damage higher than 80% in the area estimated by altitude, and 60–80% in the area estimated by mean annual temperature).

4. Discussion

Following the unintentional introduction of *C. perspectalis* in Slovakia ([27], our unpublished data), strong damage to box trees by the moth has been recorded in the southern warm regions of the country. In other Central European countries, e.g., in southern Germany, Switzerland, Austria, western Hungary and the Czech Republic, high densities of *C. perspectalis*, or heavy damage to box trees caused by this species, were similarly first observed in low elevation areas with warm climates [19,21,32].

Soon after the introduction of *C. perspectalis* in Slovakia, investigations of the moth were based on extensive (but not systematic) data recording which did not provide complex information on

the spread of *C. perspectalis* in the West Carpathians. In contrast, our data, collected systematically in a total of 156 distinct locations, showed that from 2012 to 2017 *C. perspectalis* colonized southern lowlands in Slovakia and southern parts of the valleys connected with these lowlands. We found that box trees were not damaged over a large continual area in the north of the country, characterized by higher altitudes and colder climates. Croatia, a country with similar geomorphological conditions to those found in Slovakia, was entirely colonized by *C. perspectalis* within a shorter time period of four years [40]). The fast spread of the moth was also recorded in Bulgaria [41]. This suggests better conditions for the spread of the pest in these two countries in southern Europe [21].

In most locations in Slovakia, where box trees were infested by *C. perspectalis*, the damage was high. Low and medium damage to host trees was mostly recorded in a narrow zone between 200 m and 390 m a.s.l. and was characterized by mean annual temperatures between 9.2 °C and 7.9 °C. *Cydalima perspectalis* could gradually spread to these areas as it can survive cold winter temperatures down to −25 °C (NW Switzerland) or even −30 °C (N China and E Russia) [21]. The moth could spread into cool areas actively and/or passively but the movements and the length of occurrence of the moth in these areas are unpredictable.

Our results suggested that the probability of damage to box trees by *C. perspectalis* five years after introduction in Slovakia can be estimated by using the altitude and/or the mean annual temperature of the location. These variables, and particularly altitude, can be obtained with ease by the public (e.g., via GPS functionality on a smart phone). This provides scope for the inclusion of "citizen science" in the mapping of the distribution of *C. perspectalis* and damage to box trees by this invasive pest.

The results from Slovakia also showed that the altitude and the mean annual temperature values that determined the probability of low and especially medium damage, only differ slightly from those determining the probability of high damage. Thus, the modelled area with any damage expected (low, medium, or high) was only slightly larger than that where high damage was expected.

Frequent occurrence of old box trees in the urban areas of the West Carpathians indicates intensive long-term trade with the host of *C. perspectalis*. Therefore, the moth could be passively transported everywhere where its host is present. However, we did not record any damage to box trees over large cool areas, suggesting their low suitability for the establishment of the pest. The moth can cause severe damage to box trees if it has two or more generations [21]. We found two generations of *C. perspectalis* at the locations with high damage to box trees in the central part of Slovakia [42]. Bakay and Kollár [27] reported three generations in Slovakia, and Šefrová and Laštůvka [19] two generations in Central Europe. As generations may overlap, it is difficult to identify the adult flight period clearly for each generation [43]. The number of generations in the West Carpathians, in locations with low or medium damage, is unknown. However, due to the ongoing changes in climate, weather conditions over one year or several consecutive years may enable development of two generations of the moth in the cool regions of the West Carpathians mountain range. Therefore, occasional cases of high damage to box trees in these regions in the near future are possible.

High damage to box trees, reflecting high density of *C. perspectalis*, within the colder areas with low probability of high damage was recorded only rarely. These few exceptions were the locations near the warmer areas with high probability of high damage. High density of the pest in these locations could reflect favorable weather conditions, and active or passive spread of the moth from the adjacent warmer areas. High damage to box trees in locations within the colder areas suggest the possible spread of *C. perspectalis* into higher elevated areas with colder climates.

There were also a few locations with undamaged trees within the warmer areas with high probability of high damage. These undamaged trees, possibly, were newly planted or treated with insecticides.

The maps showing the areas with probability of damage to box trees in the neighboring countries of Slovakia were made using extrapolated data from Slovakia. There is a need to verify the accuracy of these maps using data specific to these countries. The data on the occurrence of *C. perspectalis* from the neighboring countries were insufficient in certain cases. Nevertheless, the locations with

known occurrence of *C. perspectalis* in the neighboring countries by 2017 were in the areas modelled to have high probability of damage to box trees. Surprisingly, the occurrence of *C. perspectalis* in the Czech Republic was predicted more accurately by altitude than by mean annual temperature. More continental climate in Slovakia could explain this but the phenomenon requires further study.

In the hilly and mountain areas of the West Carpathians in Slovakia, *C. perspectalis* may spread actively further to the north and into higher altitudes with colder climates, using valleys as corridors, as known in other invasive species such as the harlequin ladybird *Harmonia axyridis* [44]. The valleys are densely populated; therefore, the active dispersal of adult *C. perspectalis* between villages and towns is highly likely. Adult moths are active flyers [9,17] and are able to disperse far from the hosts. For example, in the south-eastern part of the Czech Republic, adults often fly to light sources anywhere in open fields and even inside forests [19]. Their wider dispersal from towns and villages to the surrounding habitats is also supported by high densities of nectaring plants such as *Eupatorium cannabinum* and *Rubus* spp. providing food for adults [45,46]. However, the passive spread of the pest via the transportation of infested box trees should also be considered. Such spread with infested plant material is also known in other invasive species (e.g., [47–49]).

The population density of *C. perspectalis* may be reduced by insecticides which have been increasingly applied to box trees, and/or by replacing box trees by other species of evergreen shrubs. These measures may slow the spread of the moth. The numbers of *C. perspectalis* can also be locally reduced by the loss of host plants killed by the moth larvae [42].

5. Conclusions

We conclude that over a six year period (2012–2017) *C. perspectalis* became established in Slovakia in low elevated regions with warm climates, causing serious damage to box trees. However, the moth was not recorded over large colder areas of the country. The further spread of *C. perspectalis* to higher elevated and colder areas is likely, as the box trees with severe damage were found in the border zones of the known occurrence of the moth. Damage to box trees in any part of the country, resulting from the trade and movement of infested box trees, is possible. Our results suggest that the further spread of *C. perspectalis* across most of the territory of Slovakia will take longer than in the countries with warmer climates.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/11/9/0999/s1, Table S1. Inspected locations with analysed variables.

Author Contributions: Conceptualization, J.K., P.Z., and M.S.; methodology, J.K., P.Z., J.H., and P.M.J.B.; software, J.H. and J.K.; validation, J.K., P.Z., J.H., P.M.J.B., L.S., J.S., Z.M., A.H., J.V., M.H., and M.S.; formal analysis, J.K., J.H., and J.V.; investigation, J.K., P.Z., J.H., P.M.J.B., L.S., J.S., Z.M., A.H., J.V., M.H., and M.S.; resources, J.K. and P.Z.; data curation, J.K. and J.H.; writing—original draft preparation, J.K. and J.H.; writing—review and editing, J.K., P.Z., J.H., M.S., and P.M.J.B.; visualization, J.H.; supervision, P.M.J.B., J.S., Z.M., A.H., and M.S.; project administration, J.K. and P.Z.; and funding acquisition, J.K.,P.Z., M.H., P.M.J.B., J.S., Z.M., and A.H. All authors have read and agreed to the published version of the manuscript.

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