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POTENTIAL DISTRIBUTION OF THE INVASIVE SPECIES *METCALFA PRUINOSA* (HEMIPTERA, FLATIDAE) AND PERSPECTIVES OF ITS CLASSICAL BIOCONTROL IN UKRAINE

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Potential Distribution of the Invasive Species *Metcalfa pruinosa* (Hemiptera, Flatidae) and Perspectives of Its Classical Biocontrol in Ukraine. Bondareva, L. M., Kaliuzhna, M. O., Titova, L. G., Klechkovskiy, Yu. E., Perkovsky, E. E. — The study used GIS software and climatic projectors to assess the

distribution potential of the citrus planthopper *Metcalfa pruinosa* (Say, 1830) in Ukraine, taking into account global climate change. The model showed that climatic conditions in Ukraine meet the requirements of the species in the European part of its range, considering various indicators such as the sum of active temperatures, mean annual temperature and precipitation. The whole territory of Ukraine could potentially be a range for *M. pruinosa* due to suitable climatic conditions and the presence of host plants, with Zakarpattia, Crimea and the Wood-and-Steppe and Steppe zones of Ukraine being the most favourable. Current phytosanitary measures are not sufficient to prevent its spread and a pest management system is needed to reduce the damage. The parasitoid *Neodryinus typhlocybae* (Ashmead, 1893) (Hymenoptera, Dryinidae) from North America could serve as a classical biological control agent of *M. pruinosa* in Ukraine, and suitable areas for its introduction the south of the country have been identified using GIS modelling. To manage the risk effectively, it is recommended that *M. pruinosa* be added to the list of regulated, non-quarantined pests in Ukraine.
Key words: invasion, citrus flatid planthopper, *Neodryinus typhlocybae*, bioclimatic model, potential distribution

Introduction

The citrus flatid planthopper, *Metcalfa pruinosa* (Say, 1830), is one of the most important invasive species in Europe. *M. pruinosa* originates from North America, where the insects are widespread in various climatic zones from Texas and Florida through the eastern United States to southern Ontario and Quebec in Canada. Accidentally introduced from North America to Italy in 1979 (Zangheri & Donadini, 1980), *M. pruinosa* spread rapidly and is now present in almost all European countries (Metcalfa…, 2023). The citrus flatid planthopper damages important agricultural crops and fruit trees directly through phloem feeding, or indirectly by contaminating plant surfaces with waxy secretions and honeydew that induce sooty mold development, and by transmitting dangerous plant pathogens (Duso, 1984; Donati et al., 2017; Lee & Wilson, 2010; Vétek et al., 2019; Świerczewski et al., 2022).

The invasion of *M. pruinosa* has been recorded in the following countries and territories of Eurasia: Albania, Austria, Azerbaijan, Bosnia and Herzegovina, Bulgaria, Croatia, Czechia, France, Georgia, Germany, Gibraltar, Greece, Hungary, Italy, Moldova, Montenegro, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, South Korea, Spain, Switzerland, Turkey, Ukraine (Bensusan & Perez, 2011; EPPO, 2023; Karsavuran & Güçlü, 2004; Ţugulea et al., 2020). *M. pruinosa* was recorded in Great Britain in 1994, but the invasive population was successfully eradicated (Malumphy et al., 1994). The general distribution of *Metcalfa pruinosa* is shown in figure 1.

A study of the likelihood of naturalisation and spread of the citrus flatid planthopper in European countries has shown that it was first found in nurseries and open centres of ornamental horticulture, indicating that these pests is introduced into new areas through the sale of plants for planting (Malumphy, 1994). The pest

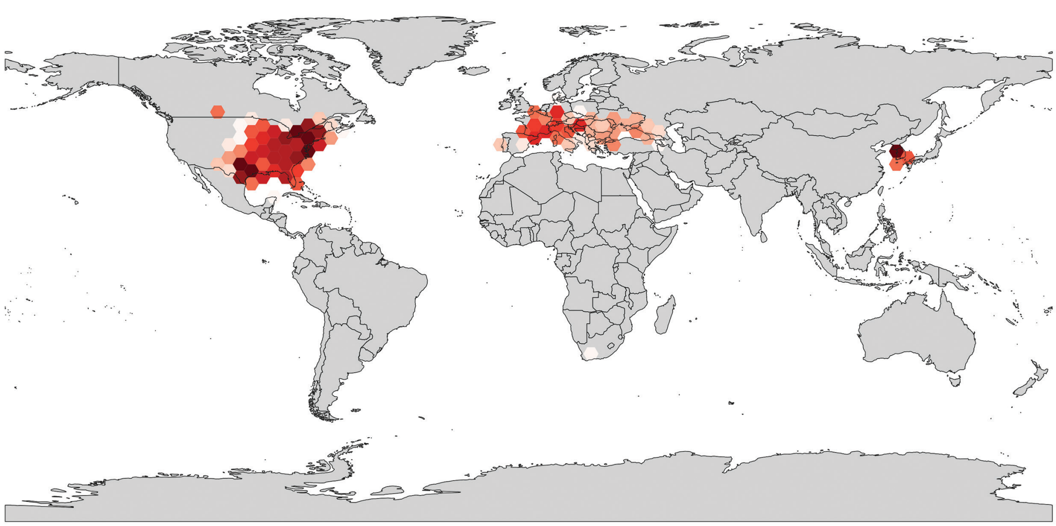

Fig. 1. Density of *M. pruinosa* occurrences in the world generated in QGIS according to GBIF data (white — low density, deep red — high density).

lays its eggs under the bark, where they are well protected during the winter. Therefore, the high survival rate of insects at the egg stage during transport and storage of plants is very likely. Another likely way for the insect to enter new territories is through the use of vehicles. *M. pruinosa* has been found along roads, bus routes, motorways, and car parks in several European countries. Passive dispersal of insects due to tourist travel in European countries during the summer holiday season can also be considered as a secondary dispersal route (Strauss, 2010).

The first record of *M. pruinosa* in Ukraine was made in 2011, when single specimens were found on the ailanthus (*Ailanthus altissima* (Mill.) Swingle) in Odesa (Uzhevskaya et al., 2012). A stable pest population formed in the Ovidiopol District of the Odesa Region, which was detected during the inspection of plantings of fruit, ornamental and vegetable crops (Popova et al., 2019). Since the first reports of its appearance in 2011, the citrus flatid planthopper has rapidly acclimatized and spread in Ukraine, causing severe damage to various agricultural crops (Popova et al., 2019; Yanse & Sus, 2023). Incursions of the citrus flatid planthopper have been found in the cities of Donetsk (Martynov & Nikulina, 2018), Simferopol (Stryukova & Stryukov, 2020), Kyiv (Kushnir & Bondareva, 2022; Yanse & Sus, 2023), in Vynogradiv and Uzhgorod districts of the Zakarpattia Region, and in Kharkiv and Dnipropetrovsk Regions (UkrBIN, 2023). Currently, *M. pruinosa* has been recorded in ten regions of Ukraine (fig. 2), but the pest may also occur in other areas, e. g. in Rivne Region (M. R. Khomych, pers. com., 2022).

Such simultaneous detection of the pest in different areas of the country can cause rapid spread of this phytophagous species and requires rapid development of the control system and measures to prevent its spread, which should be based on the forecast of the possibility of acclimatisation and determination of a potential distribution of *M. pruinosa* in Ukraine. It is known that the cause of the spread of phytophagous species and changes in their range is primarily unintentional human activities and global climate changes. One of the main requirements for the establishment of a species in a new area is the correspondence of climatic conditions with those requirements of the existing area. For this purpose, the analysis of climatic types of the European part and Ukraine for the range of *M. pruinosa* was carried out.

Since *M. pruinosa* has more than 300 species of host plants in Europe (Wilson & Lucchi, 2001), it may be recorded in all regions of Ukraine with suitable environmental conditions for the species (especially climatic and bionomic [availability of host plants]). On the territory of the M. M. Hryshko National Botanical Garden, NASU (Kyiv) *M. pruinosa* damages 80 plant species of 55 families (Kushnir & Bondareva, 2022). The high ecological plasticity of the citrus flatid planthopper can represent a phytosanitary danger.

The occurrence of *M. pruinosa* in Ukraine and the high potential harmfulness of this species cause the necessity to identify the territories of Ukraine suitable for further spread and establishment of this pest and to determine the potential area within the framework of the Phytosanitary Risk Analysis (PRA) procedure based on

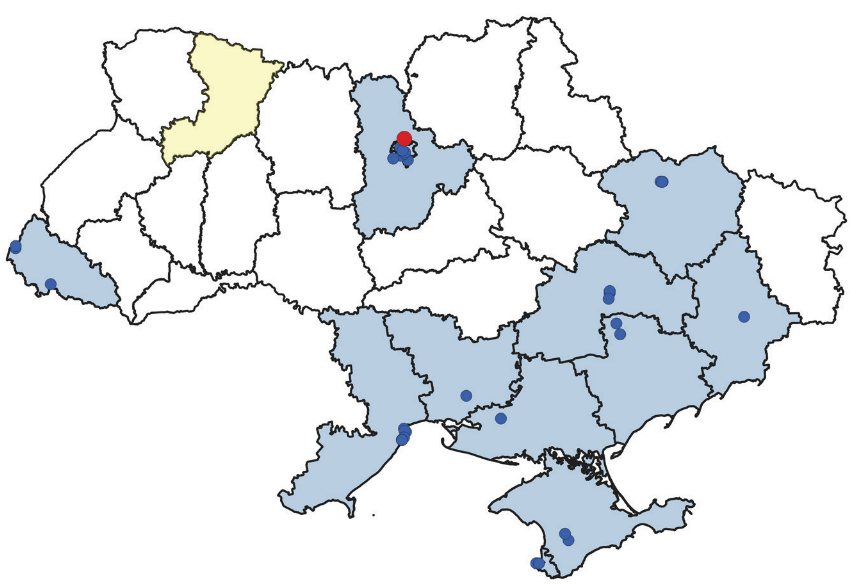

Fig. 2. Previously known records of *M. pruinosa* in Ukraine marked blue; Rivne Region with possible findings of *M. pruinosa* marked yellow; the original data on the northeasternmost locality marked red.

GIS modelling using modern software and bioclimatic predictors. Bioclimatic modelling has been successfully used for other invasive species in Ukraine, such as *Diabrotica virgifera virgifera* Le Conte, 1858, *Oemona hirta* (Fabricius, 1775), *Thaumatotibia leucotreta* (Meyrick, 1913), *Grapevine roditis leaf discoloration-associated virus* (Klechkovskiy et al., 2016, 2022; Titova et al., 2017, 2020).

Technologies of ecological and geographical analysis and modelling of the distribution of biological objects are widely used in the world to make predictions about the distribution of harmful objects. Several models have been used by researchers to predict the spread of the citrus psyllid beyond its existing range. In Austria, the CLIMEX programme was used to determine the geography of the potential distribution of the accidentally introduced *M. pruinosa* in Europe and the areas of phytosanitary risk. The zones with the most suitable climate for the development of the pest and the risk of its introduction were identified (Strauss, 2010). CLIMEX software was used to predict the spread of *M. pruinosa* in South Korea (Byeon et al., 2017) and on a global scale (Byeon et al., 2018). MaxEnt algorithm was used to model the process of pest range expansion and predicted the potential spread of this species in the Republic of Korea (Kim et al., 2019).

Chemical control of *M. pruinosa* is difficult because this species is polyphagous, its nymphs have a prolonged hatching period and are covered by the waxy secretion during development, in addition, treatment with the pesticides effective against *M. pruinosa* could cause additional ecological problems in urban and agroecosystems (Vétek et al., 2019). One of the solutions for the regulation of *M. pruinosa* is biocontrol with its natural enemy, the parasitoid *Neodryinus typhlocybae* (Ashmead, 1893) (Hymenoptera, Dryinidae). This species also originates from North America and is now spreading in Europe (Vétek et al., 2019). A targeted search for *N. typhlocybae* is highly recommended in those regions where *M. pruinosa* is present and has been established, but *N. typhlocybae* has not yet been recorded (Vétek et al., 2019). GIS modelling could help to assess the suitability of the territory of Ukraine for *N. typhlocybae* and facilitate further search for this parasitoid in our country.

Our research is focused on identifying the potential range of *M. pruinosa* on the territory of Ukraine and the bioclimatic factors contributing to the spread of the pest, as well as assessing the suitability of different areas of Ukraine for *M. pruinosa* and its natural enemy, *N. typhlocybae*, in the perspective of climate change and the possibilities of using this entomophage for classical biocontrol of the citrus flatid planthopper.

Material and Methods

1. Modelling the potential range of *M. pruinosa* in Ukraine

Identification of the potential range of *M. pruinosa* in Ukraine was carried out using the computer programs AgroAtlas (Shumilin & Li, 2009), MapInfo Pro15.0 (ESTIMap®), and IDRISI Selva (Clark Labs®), which allow to create predictive maps of the spread of adventitious organisms in an automated mode (Afonin & Li, 2011; Titova & Klechkovskyi, 2014; Borzykh et al., 2018).

For this purpose, several consecutive operations were performed:

1. Construction of the vector map of the European part of the range of *M. pruinosa* in the MapInfo Pro15.0.
2. Export of the constructed vector map of the European part of the range of *M. pruinosa* to the program IDRISI Selva.
3. Determination of the average multi-year indicators of climatic factors in different parts of the European range on world climate maps (average annual temperature, sum of active temperature — SAT (> 10 °C), temperatures of the warmest and coldest months, average annual precipitation).
4. Determination of maximum and minimum indicators in the quantitative amplitudes of each of the limiting factors.
5. Determination of the suitability of the climatic conditions of the territory of Ukraine for the existence of the species for each of the individual climatic indicators.
6. Construction of vector maps of ecologically suitable areas for each of the limiting factors on the climatic maps of AgroAtlas.

Construction of the map of the potential range of *M. pruinosa* in Ukraine, by the operation of superimposing of three vector maps of ecologically suitable areas as a result of which the area suitable for the existence of the species is determined by a set of climatic factors.

Long-term mean values of climate indicators in different parts of the European range of the pest were determined on world climate maps, and maximum and minimum values of quantitative amplitudes for each of the limiting factors were determined. The data of the conducted GIS analysis were used to determine the acceptable climatic conditions in Ukraine for the existence of *M. pruinosa* and to construct vector maps of ecologically suitable areas for each of the limiting factors. The maximum and minimum values of ecological amplitudes in the European part of the range were used (table 1).

Table 1. Indicators of amplitudes of fluctuations of climatic predictors in different places of the European part of the range of *Metcalfa pruinosa*

SAT, >10, T °C	1635; 1882; 2010; 2030; 2124; 2187; 2430; 2582; 2639; 2706; 3384; 3550; 3550; 3597; 3857; 6189; 6266; 6481.
Average annual temperature, T °C	3.5; 3.8; 4.4; 6.3; 7.2; 7.4; 7.7; 7.8; 9.1; 9.3; 10.1; 10.4; 12.7; 13.3; 13.8; 14.7; 15.7; 17.2; 17.8; 18.2; 19.5.
Temperatures of the warmest month, T °C	15.3; 15.9; 16.4; 16.7; 16.8; 17.1; 17.5; 18.6; 19.1; 20.3; 20.6; 20.6; 22.6; 23.2; 23.4; 24.2; 24.5; 25.2; 25.3; 26.2; 26.3; 26.5.
Temperatures of the coldest month, T °C	−16.2; −15.1; −15.1; −12.8; −12.0; −11.8; −10.9; −10.8; −9.2; 7.9; −6.1; −5.5; −4.2; −3.9; −3.7; −3.0; −2.4; −1.9; −1.7; −1.3; −1.0; 0.
Average annual precipitation, mm	158; 387; 409; 471; 482; 506; 515; 516; 525; 543; 543; 563; 575; 612; 639; 645; 646; 665; 704; 736; 764; 764; 799; 841; 871; 1088; 1360; 1487; 2046.

The creation of a digital vector map of the potential area, carried out usi ng of the AgroAtlas, MapInfo Pro 15.0, and IDRISI SELVA software, allows the climatic acceptability of the territory of Ukraine for *M. pruinose* to be represented graphically. At the same time, the subjective factor is completely excluded, since the boundaries of the area are determined by the program on the the basis of biological characteristics of the object.

The IDRISI SELVA program eliminates areas that do not meet the required parameters, which allows to systematize all data and to clearly predict possible areas of acclimatization and spread of the pest. Areas that are not suitable for the existence of the species are coloured black, while areas that are suitable for each of the analyzed climatic factors and potential range are coloured by the program.

2. Modelling of *M. pruinosa* distribution under current and future climate conditions

Species occurrence data. Occurrence data for GIS modelling were obtained from open databases (GBIF, https://doi.org/10.15468/dl.wsusek, accessed March 9, 2023, 9984 occurrences; UkrBIN, https://ukrbin.com/index.php?id=360335&action=distribution, accessed October 21, 2022, 21 occurrences) and 1 original occurrence data was used: Ukraine: Kyiv Reg.: Vyshgorod District [50.624250 N, 30.538195E], 30.08.2022, 1 ♀ (Perkovsky). Specimen is preserved in I. I. Schmalhausen Institute of Zoology of National Academy of Sciences of Ukraine (SIZK). In total, we started with 10,006 occurrences, and this data set was reduced to improve the quality of the modelling.

Data preparation. To perform the modelling, we reduced the sample of the species occurrence data. First of all, we discarded points for which the coordinate accuracy was too low, in particular, we excluded all occurrences for which in GBIF the coordinate uncertainty was greater than 4.63 km, in order to correlate the spatial resolution of the occurrence points with the chosen spatial resolution of the layers of bioclimatic factors (2.5 minutes). After this manipulation we received 8946 occurrences. Then, using the spThin package in R, we reduced the sample to keep only the points that were at least 10 km apart. Finally, we obtained a data set with 2292 occurrences for modelling (fig. 3).

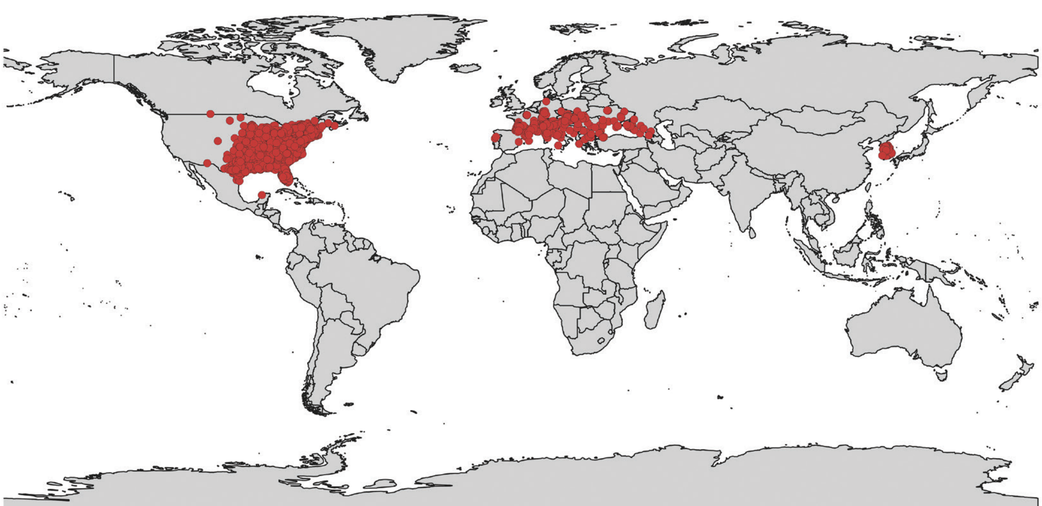

Fig. 3. World occurrence data on *M. pruinosa* used in this study.

Table 2. 19 bioclimatic variables, used for MaxEnt modelling

BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp-min temp))
BIO3	Isothermality (BIO2/BIO7) (×100)
BIO4	Temperature Seasonality (standard deviation ×100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5/BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

Ecological niche modelling. Detalization of a suitability of the territory of Ukraine for *M. pruinosa* in a current and future climate was conducted using Maximum Entropy modelling (Phillips et al. 2004, 2006) in MaxEnt, version 3.4.3. with default settings. We used 19 bioclimatic variables of historical climate data (1970-2000) (Fick & Hijmans, 2017) and future climate CMIP6 model CanESM5-CanOE (2024-2060) (WorldClim.org, accessed March 1, 2023) with spatial resolution 2.5 minutes and the shared socio-economic pathway (ssp) 245. The results were represented using the logistic threshold output format. Received maps were then processed in QGis 3.28.4-Firenze (table 2).

Model analysis. To assess model quality, we used built-in measures such as omission rate and area under the ROC curve (AUC). For the analysis of variable contributions, we used data on percent contribution, permutation importance, and performed the jackknife test. We considered that characteristics such as percent contribution should be interpreted with caution (Phillips, 2017; Songer et al., 2012).

3. Modelling the distribution of *N. typhlocybae* under current and future climate conditions

Occurrence data for *N. typhlocybae* from GBIF (https://doi.org/10.15468/dl.hqzvay) were used for MaxEnt modelling with the same parameters as for *M. pruinosa*. There were 238 occurrences present in the dataset, however only 25 of them were unique localities. We tried to add an additional 40 localities with coordinates provided by Vétek et al. (2019) for Hungary, but the addition of these points caused significant changes in the model, as the points were very densely located compared to the available world data and that factor caused a strong influence, therefore, we used for modelling only GBIF data.

Results

The northeasternmost locality of *M. pruinosa* and information on biology of species

In this article we report the northeasternmost record of *M. pruinosa* for Europe. Specimens were found in countryside in Vyshgorod District of Kyiv Region, N50.624250, E30.538195, on August 30th, 2022. The specimen was found on the underside of a buckthorn leaf. *M. pruinosa* skins have also been found on *Corylus* sp. and *Robinia pseudoacacia* (fig. 4).

Under the conditions of Kyiv *M. pruinosa* develops in one generation. Mature specimens are found from July to the end of August, with mass occurrence in the middle and third part of July (fig. 5).

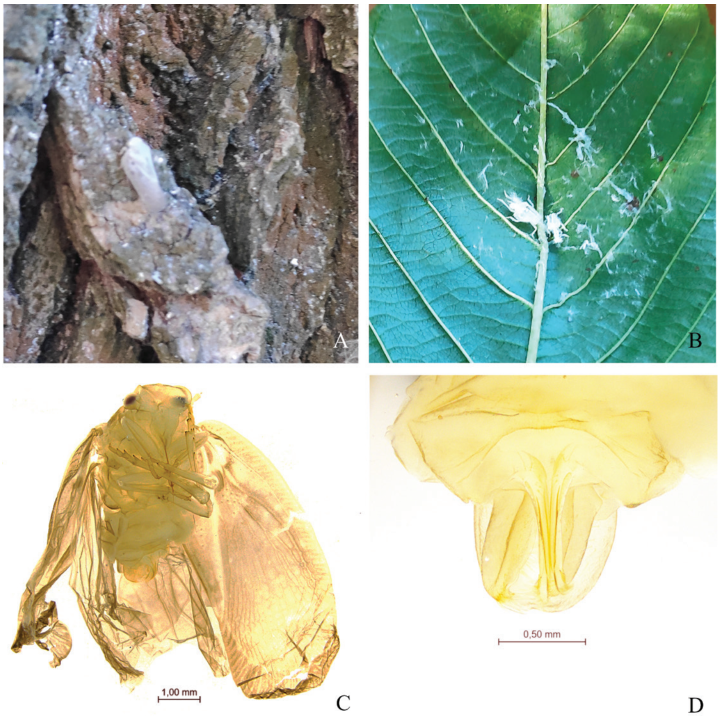

Fig. 4. *M. pruinosa* from the northeasternmost locality (Kyiv region): A — imago; B — moulting skins of citrus planthoppers; C — imago (♀) preserved in ethanol; D — details of the genitalia morphology.

Fig. 5. *M. pruinosa* in Kyiv: A — imago; B — group of citrus planthoppers; C — colony of larvae feeding on weeds.

Modelling of *M. pruinosa* potential range in Ukraine

The constructed vector maps show that the climatic conditions throughout Ukraine meet the living conditions of the species by a number of indicators: the sum of active temperatures (SAT10), the multi-year average annual temperature, the multi-year average annual temperatures of the coldest (January) and warmest (July) month, the average annual amount of precipitation (fig. 6, A, B, C, D, E, F).

As a result, by combining into a single map of climatically suitable for each of the limiting factors, the potential range of *M. pruinosa*, occupying the entire territory of Ukraine, was determined (fig. 6, F).

Modelling of *M. pruinosa* distribution under current and future climatic conditions

Under current climatic conditions. MaxEnt modelling for *M. pruinosa* confirmed that the entire territory of Ukraine is generally suitable for the citrus flatid planthopper.

Ukraine current climate is suitable for *M. pruinosa* from low to medium level: the predicted probability value in grid cells varies from 0.01 to 0.55. The area under the ROC curve (AUC) is 0.898.

Western part of Zakarpattia Region, the areas of Wood-and-Steppe and Steppe zones (except for the part of the Black Sea Lowlands) of Ukraine, and Crimea are the most favourable for the citrus flatid planthopper in modern climatic conditions in Ukraine (fig. 7).

Six bioclimatic factors accounted for 95 % of percentage contribution in building of the model: bio 17 (34.8), bio 14 (27.0), bio 5 (12.3), bio 4 (10.4), bio 12 (6.3), bio 10 (4.2). At the same time the 94 % of the permutation importance was due to the following six bioclimatic factors: bio 10 (55.3), bio 17 (23.5), bio 4 (5.3), bio 12 (3.6), bio 11 (3.5), bio 5 (2.8). As we can see bio 17, bio 10, bio 4, bio 12 contributed in both characteristics, while bio 17 (Precipitation of Driest Quarter) has the highest value in the percentage contribution, and bio 10 (Mean Temperature of Warmest Quarter) has the highest value in the permutation importance (table 3).

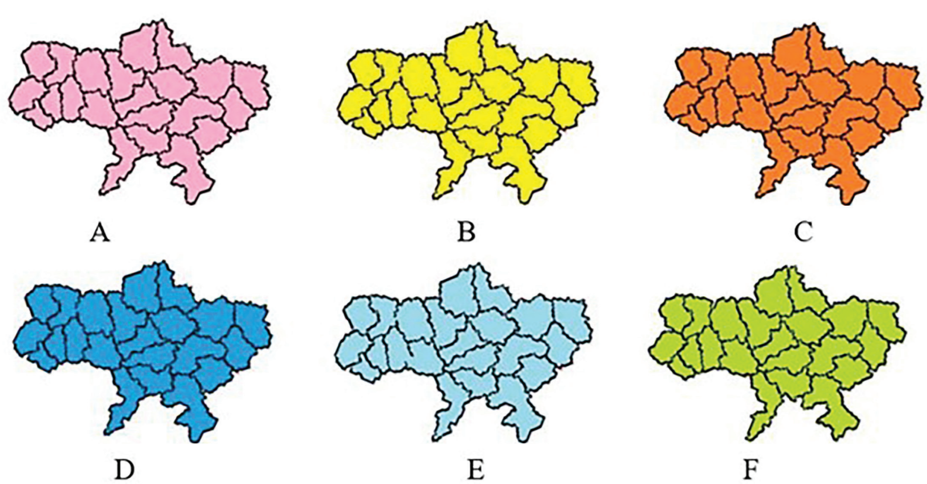

Fig. 6. Territories of Ukraine that meet the climatic preferences of *M. pruinosa* by indicators: A — sum of active temperatures (SAT10); B — average annual temperature; C — average annual temperature of the warmest month (July); D — average annual temperature of the coldest month (January); E — average annual amount of precipitation; F — potential range of *M. pruinosa*.

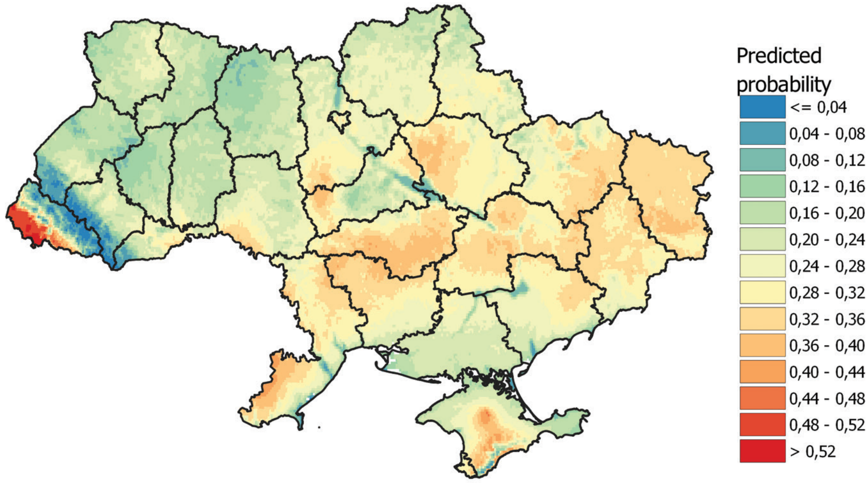

Fig. 7. Modelling of suitability of the current bioclimatic conditions of Ukraine for *M. pruinosa*. Predicted occurrence probability for the species marked from the lowest — blue, to the highest — red.

The jackknife test of variable importance showed that the environmental variable with highest gain when used in isolation was bio 17, which therefore appears to have the most useful information by itself, and the environmental variable that decreases the gain the most when it is omitted is bio 10, which therefore appears to have the most information that isn't present in the other variables.

Under future climatic conditions the suitability of the territory of Ukraine remains favourable at medium and low levels: grid cells values range from 0.01 to 0.52. The area under the ROC curve (AUC) is 0.898.

The most suitable areas remain almost the same with a slight improvement of suitability in more northern territories, e. g. south of the Kyiv Region, north-western part of Poltava Region, northern part of Kharkiv Region. There is a certain redistribution of more suitable areas: the suitability becomes more homogeneous, with a lower grid cell value, however, a larger area becomes more satisfying to the ecological preferences of *M. pruinosa* (fig. 8).

Nine bioclimatic factors formed 97.7 % of the percentage contribution in building of the model: bio 17 (41.3), bio 14 (19.1), bio 5 (17.3), bio 4 (11.6), bio 12 (2.3), bio 1 (1.9), bio 11 (1.7), bio 10 (1.3), bio 18 (1.2). While 97.2 % of the permutation importance

Table 3. Analysis of variable contributions to the modelling of suitability of the current bioclimatic conditions of Ukraine for *M. pruinosa*

Variable	Percent contribution	Permutation importance
Bio 17	34.8	***23.5***
Bio 14	27.0	0.1
Bio 5	12.3	2.8
Bio 4	10.4	5.3
Bio 12	6.3	3.6
Bio 10	4.2	***55.3***
Bio 7	1.5	0.1
Bio 3	1.2	1.9
Bio 9	0.7	0.4
Bio 6	0.7	0.0
Bio 18	0.5	0.5
Bio 16	0.2	0.2
Bio 2	0.1	0.9
Bio 13	0.1	1.6
Bio 1	0.1	0.2
Bio 11	0.0	3.5
Bio 8	0.0	0.0
Bio 15	0.0	0.0
Bio 19	0.0	0.0

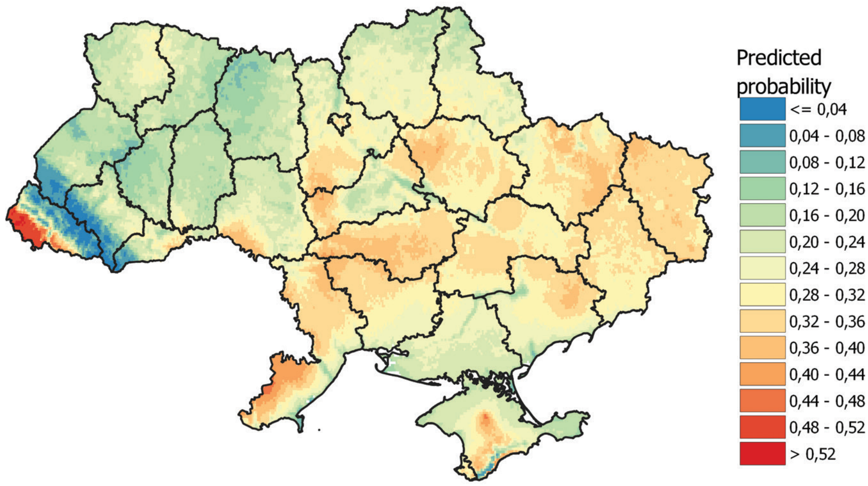

Fig. 8. Modelling of suitability of the future bioclimatic conditions of Ukraine for *M. pruinosa*. Predicted occurrence probability for the species marked from the lowest — blue, to the highest — red.

was obtained due to the following eight bioclimatic factors: bio 10 (40.6), bio 17 (28.8), bio 11 (11.0), bio 5 (6.2), bio 4 (3.7), bio 16 (3.1), bio 2 (2.1), bio 12 (1.7). As we can see bio 17, bio 10, bio 11, bio 12, bio 4, bio 5 contributed in both characteristics, while bio 17 (Precipitation of Driest Quarter) has the highest value in percentage contribution, bio 10 (Mean Temperature of Warmest Quarter) has the highest value in permutation importance (table 4).

The jackknife test of variable importance also detected an important role of bio 17, when used in isolation, and bio 10, when it was omitted.

Table 4. Analysis of variable contributions to the modelling of suitability of the future bioclimatic conditions of Ukraine for *M. pruinosa*

Variable	Percent contribution	Permutation importance
Bio 17	41.3	***28.8***
Bio 14	19.1	0.0
Bio 5	17.3	6.2
Bio 4	11.6	3.7
Bio 12	2.3	1.7
Bio 1	1.9	0.3
Bio 11	1.7	11.0
Bio 10	1.3	***40.6***
Bio 18	1.2	0.7
Bio 2	0.7	2.1
Bio 7	0.6	0.1
Bio 6	0.6	0.0
Bio 16	0.4	3.1
Bio 3	0.0	1.4
Bio 8	0.0	0.0
Bio 13	0.0	0.0
Bio 9	0.0	0.0
Bio 15	0.0	0.0
Bio 19	0.0	0.0

The redistribution of the suitability of the territory of Ukraine for the *M. pruinosa* is clearly visible on the map below (fig. 9), where the difference between the current and future climate models is presented. Areas of decreasing suitability are shown in orange, and areas of increasing suitability are shown in green.

We can observe a redistribution of the suitability of regions of Ukraine for *M. pruinosa*: the suitability is increasing in Volyn, Kyiv, Cherkasy, Odesa, Kherson, Zaporizhzhia, most part of Rivne, Chernihiv, Poltava, Kharkiv Regions; the suitability of territories in Zakarpattia Region, Crimea, Khmelnytskyi Region, most part of Lviv, Ivano-Frankivsk, Ternopil, Zhytomyr, Dnipro, parts of Vinnytsia, Kropyvnytskiy, Donetsk, Luhansk, Poltava, Kharkiv regions is decreasing (fig. 9).

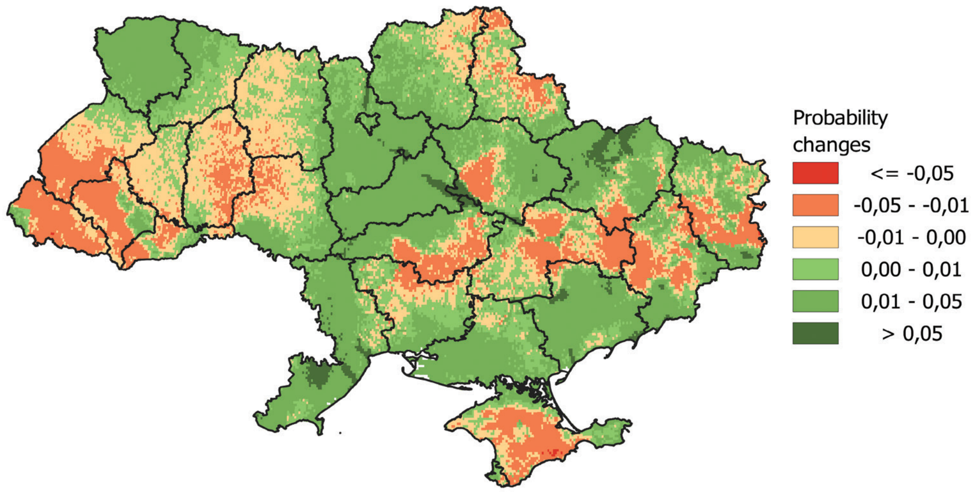

Fig. 9. Difference in suitability of the territory of Ukraine for *M. pruinosa* under future climatic conditions. Orange — areas of decreasing suitability; green — areas of increasing suitability.

Modelling of *N. typhlocybae* distribution under current and future climatic conditions

Under current climatic conditions. MaxEnt modelling for *N. typhlocybae* shows that the territory of Ukraine is suitable for this species: grid cell values range from 0.00 to 0.87. The area under the ROC curve (AUC) is 0.992.

The most favourable conditions are particularly in the south regions of Ukraine: Odesa, Mykolaiv, Kherson, Crimea, as well as Dnipro, Poltava, Kharkiv, Luhansk, and partly Kirovohrad and Zakarpattia regions (fig. 10).

Twelve bioclimatic factors constituted 96.8 % of the percentage contribution in building of the model: bio 17 (25.4), bio 19 (15), bio 11 (13.7), bio 4 (10.4), bio 15 (9.3), bio 6 (5.7), bio 18 (5.1), bio 10 (3.5), bio 2 (3.1), bio 3 (2.6), bio 1 (1.5), bio 8 (1.5). At the same time 97 % of permutation importance was due to following ten bioclimatic factors: bio 6 (39.3), bio 15 (33.3), bio 10 (9.0), bio 18 (4.3), bio 11 (3.9), bio 8 (2.5), bio 2 (1.5), bio 13

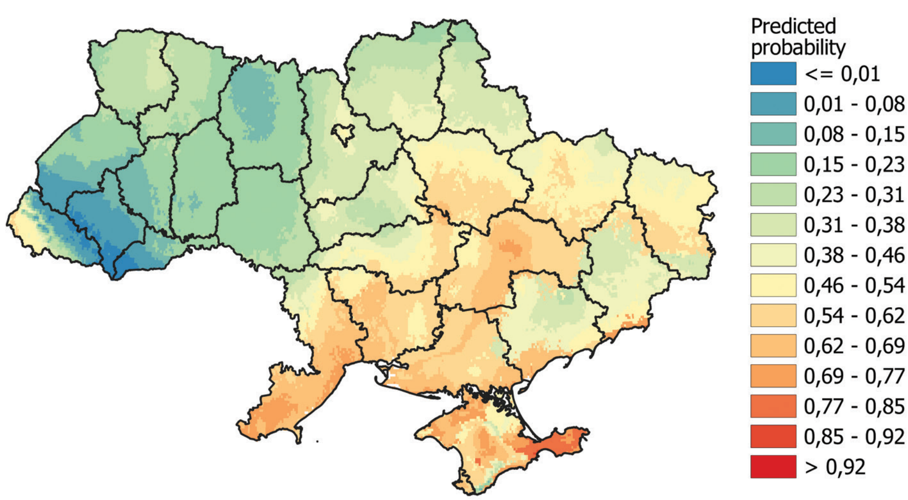

Fig. 10. Modelling of suitability of the current bioclimatic conditions of Ukraine for *N. typhlocybae.* Predicted occurrence probability for the species marked from the lowest — blue, to the highest — red.

Table 5. Analysis of variable contributions to the modelling of suitability of the current bioclimatic conditions of Ukraine for *N. typhlocybae*

Variable	Percent contribution	Permutation importance
Bio 17	25.4	0.0
Bio 19	15.0	0.6
Bio 11	13.7	3.9
Bio 4	10.4	0.0
Bio 15	9.3	***33.3***
Bio 6	5.7	***39.3***
Bio 18	5.1	4.3
Bio 10	3.5	9.0
Bio 2	3.1	1.5
Bio 3	2.6	0.9
Bio 1	1.5	0.8
Bio 8	1.5	2.5
Bio 13	1.3	1.4
Bio 9	1.3	0.6
Bio 5	0.4	0.6
Bio 16	0.1	0.9
Bio 12	0.1	0.1
Bio 14	0.1	0.4
Bio 7	0.0	0.0

(1.4), bio 3 (0.9), bio 16 (0.9). As we can see bio 10, bio 11, bio 15, bio 18, bio 2, bio 3, bio 6, bio 8 contributed in both characteristics, while bio 17 (Precipitation of Driest Quarter) has the highest value in percentage contribution, bio 6 (Min Temperature of Coldest Month) has the highest value in permutation importance (table 5). Bio 15 (Precipitation Seasonality) has the second highest value of permutation importance — 33.3, it is very close to bio 6 (39.3).

According to the jackknife test of variable importance, the environmental variable that seems to be the most useful by itself is bio 11 (Mean Temperature of Coldest Quarter), and the environmental variable that decreases the gain the most when it is omitted is bio 18 (Precipitation of Warmest Quarter), which means it has the most information that isn't present in the other variables.

Under future climatic conditions the suitability of the territory of Ukraine for *N. typhlocybae* changes: the most noticeable change is the increase of suitability of Zaporizhzhia, Donetsk and part of Luhansk Regions. The area suitable for *N. typhlocybae* increases; however, there is some redistribution of suitability of the territories. Grid cell values of predicted occurrence probability range from 0.00 to 0.87. The area under the ROC curve (AUC) is 0.991.

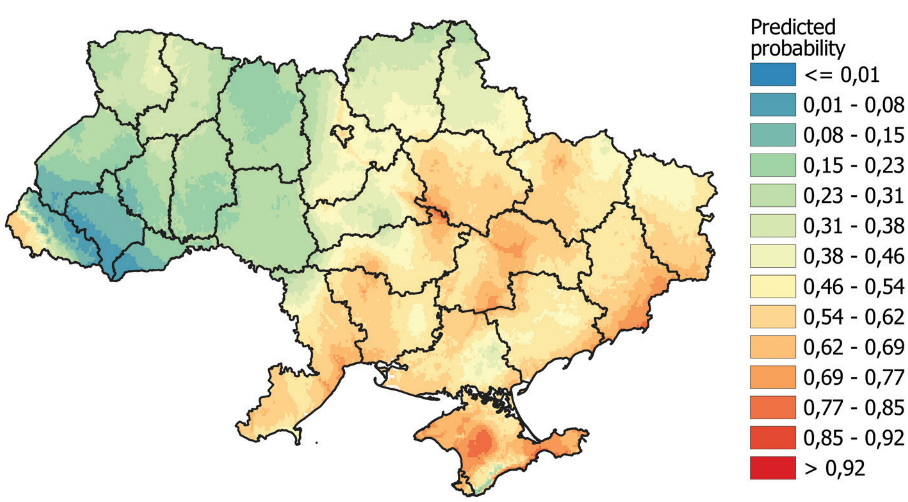

Fig. 11. Modelling of suitability of the future bioclimatic conditions of Ukraine for *N. typhlocybae*. Predicted occurrence probability for the species marked from the lowest — blue, to the highest — red.

Ten bioclimatic factors accounted for 97.5 % of the percentage contribution to the model building: bio 17 (25.4), bio 19 (16.8), bio 6 (15.9), bio 4 (11), bio 15 (10.1), bio 5 (7.3), bio 18 (4), bio 10 (3.3), bio 2 (2.6), bio 3 (1.1). While 98.5 % of the permutation importance were due to the following eight bioclimatic factors: bio 15 (35.3), bio 6 (33.8), bio 3 (14.1), bio 5 (7.9), bio 10 (3.7), bio 19 (1.3), bio 18 (1.2), bio 16 (1.2). As we can see bio 10, bio 15, bio 18, bio 19, bio 3, bio 5, bio 6 contributed in both characteristics, while bio 17 (Precipitation of Driest Quarter) has the highest value in percentage contribution, bio 15 (Precipitation Seasonality) has the highest value in permutation importance (table 6), closely followed by bio 6 (Min Temperature of Coldest Month).

Table 6. Analysis of variable contributions to the modelling of suitability of the future bioclimatic conditions of Ukraine for *N. typhlocybae*

Variable	Percent contribution	Permutation importance
Bio 17	25.4	0.0
Bio 19	16.8	1.3
Bio 6	15.9	***33.8***
Bio 4	11.0	0.0
Bio 15	10.1	***35.3***
Bio 5	7.3	7.9
Bio 18	4.0	1.2
Bio 10	3.3	3.7
Bio 2	2.6	0.0
Bio 3	1.1	14.1
Bio 1	0.9	0.0
Bio 9	0.4	0.2
Bio 8	0.4	0.2
Bio 16	0.3	1.2
Bio 13	0.3	0.4
Bio 14	0.1	0.4
Bio 12	0.1	0.1
Bio 11	0.0	0.3
Bio 7	0.0	0.0

The results of the jackknife test of variable importance shows that bio 11 (Mean Temperature of Coldest Quarter) gives highest gain when used in isolation and therefore appears to have the most useful information by itself. Bio 15 (Precipitation Seasonality) decreases the gain the most when it is omitted, which means that it has the most information that isn't present in the other variables.

As we can see on figure 12, the suitability of the territories in Rivne and Chernihiv regions in the north, areas in the centre, northeast and southeast is increasing. The suitability also increases partly in Crimea and Zakarpattia Region. At the same time, the suitability of

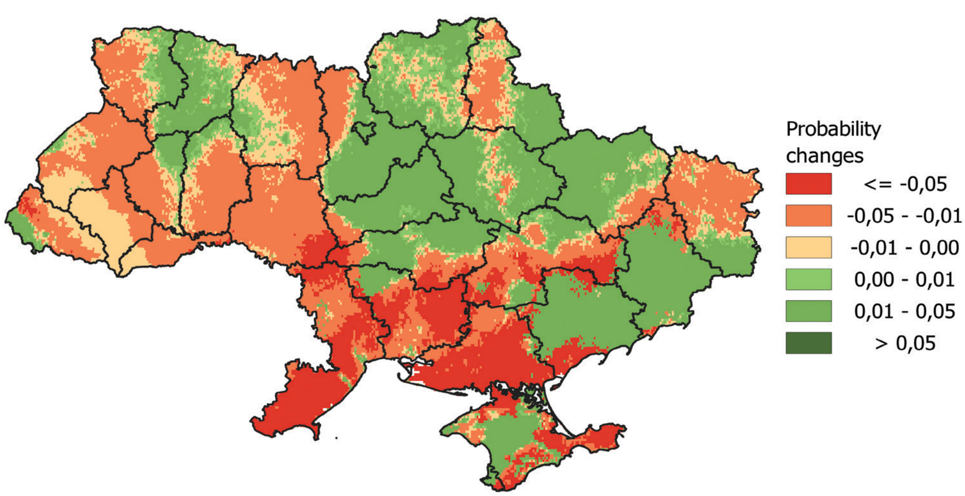

Fig. 12. Difference in suitability of the territory of Ukraine for *N. typhlocybae* under future climatic conditions. Red and orange — areas of decreasing suitability, green — areas of increasing suitability.

the most territories in the west and especially in the southwest is decreasing, as well as the sustainability of the most part of Luhansk Region and the border areas between Kharkiv and Donetsk regions, and part of Dnipro Region (fig. 12).

Discussion

The territory of Ukraine is in general moderately suitable for the existence of the citrus flatid planthopper, due to the characteristics of Ukrainian climate (Marynych & Shyshchenko, 2005; Zatula & Zatula, 2013; Ukraine…, 2023) that meets physiological demands of the species (Strauss, 2010). Nevertheless, under current climatic conditions the territory of the Wood-and-Steppe and Steppe zones (except for the part of the Black Sea Lowland), Zakarpattia Region, and Crimea are more suitable for *M. pruinosa* than other territories. Under future climatic conditions used in the study the most appropriate areas for the citrus flatid planthopper largely stay consistent, with a slight enhancement in suitability observed in the northern areas. This trend corresponds with the results of Byeon et al. (2018), who showed that the distribution of *M. pruinosa* would likely shift northward across North America and Europe. Also, under future climatic conditions, a redistribution of more favourable areas is evident: suitability becomes more uniform, indicated by decreasing grid cell values and an increase in the area that better matches the ecological preferences of *M. pruinosa*. Such potential decrease of suitability of the territory in future was as well shown for South Korea, that was explained by the temperature increase due to climate change (Byeon et al., 2017).

The important influence of temperature can also be seen from the analysis of the factors in MaxEnt: the Mean Temperature of Warmest Quarter (bio 10) is the main contributor in the model permutation importance. Another important factor is the Precipitation of Driest Quarter (bio 17) that has the highest value in percentage contribution in the model. These two factors were distinguished by all methods of variable contribution analysis, including jack knife. The following factors as Mean Temperature of Coldest Quarter (bio 11), Max Temperature of Warmest Month (bio 5), Temperature Seasonality (bio 4), as well as Annual Precipitation (bio 12) also play an important role.

Abiotic factors of the environment have a significant effect on the citrus flatid planthopper. Studies have shown that day and night air temperatures, the amount of precipitation and their duration were crucial in the rate of insect development (Strauss, 2010; Kim et al., 2019; Popova et al., 2019). The development of the pest is limited by a minimum and maximum air temperature. The minimum threshold defined by G. Strauss (2010) is 13°C according to observed distribution of *M. pruinosa* in North America. Study based in Kyiv showed that temperature of 17–20 °C in May and August–September can limit the development of the citrus flatid planthopper, while the first imagoes rear at minimum night temperature 22 °C (Kushnir & Bondareva, 2022), that corresponds with the lower optimal temperature of 22 °C found by G. Strauss (2010). The maximum temperature threshold for *M. pruinosa* development is 31 °C (Strauss, 2010), that is why the Max Temperature of Warmest Month (bio 5) is also a very important factor, that was confirmed by our study and by Kim et al. (2019), who also used MaxEnt. This could explain why our model predicts a decrease in suitability for *M. pruinosa* in Crimea, which already has high subtropical temperatures (Marynych & Shyshchenko, 2005).

The annual precipitation affects the *M. pruinosa* less than some other temperature or precipitation indicators, because according to this factor, most suitable areas should be located in the west and northwest of Ukraine and in the Carpathians, however, according to our modelling results it is not so. Strauss (2010) showed that *M. pruinosa* has a limited distribution in dry regions, however, Kushnir and Bondareva (2021) reported that heavy rains together with lowering of the temperature could lead to rapid decrease of species population that was observed in July–August 2019 in the M. M. Gryshko National Botanical Garden of National Academy of Sciences of Ukraine in Kyiv. Modelling of global geographic distribution of *M. pruinosa* using CLIMEX (Byeon et al., 2018) showed that ecoclimatic index and, therefore, probability of species distribution was higher in western part of Ukraine then in the south or east, however, the region of Carpathians and Volyn Region were marked as less suitable. Our research shows that Northern and Western Ukraine (except Zakarpattia Region) is less suitable for *M. pruinosa* then south and south-east territories, although due to predicted climate changes, the suitability of the territory of Volyn, Kyiv, parts of Rivne, Zhytomyr and Chernihiv regions will somewhat increase. We assume the use of another set of predictors with different spatial resolutions as well as another modelling method could explain this difference, and it should be noted that maps obtained by Byeon and coauthors were quite generalized and not specifically paid attention to the territory of Ukraine, but rather trying to show main world trends. Among the factors associated with precipitation, according to our data, an important role is played by the Precipitation of Driest Quarter (bio 17), which apparently works as a limiting factor together with the Mean Temperature of Warmest Quarter (bio 10).

It is worth noting that the predicted probability of finding *M. pruinosa* is at the medium level, in particular, the value does not exceed 0.52, which may mean that other factors that were not included in the analysis also affect the spread of the citrus planthopper. These may be anthropogenic factors, such as the spread with transport and plant material (Lee & Wilson, 2010). Modelling results of spreading *M. pruinosa* in South Korea, conducted with the help of MaxEnt, justified that the rapid spread of the pests besides ecological factors is strongly connected with anthropogenic factors (Kim et al., 2019).

Biotic factors are important as well. The wide range of citrus flatid planthopper host plants also serves as reserves for this invader species, with only woody plants serving as overwintering sites (Kim et al., 2011), so forest strips play an important role for overwintering and subsequent increase in *M. pruinosa* populations, especially on field crops. This is also a favourable factor for the spread of citrus flatid planthopper in the Wood-and-Steppe zone of Ukraine.

The areas we have identified as favourable for the citrus flatid planthopper settlement are precisely those regions where horticulture and viticulture are developed in Ukraine (Plant Growing…, 2021). Accordingly, attention should be paid to controlling *M. pruinosa* in these regions to reduce potential damage to orchards and vineyards.

One of the methods of controlling *M. pruinosa* is the possibility of biological control with the help of a natural enemy, the parasitoid *N. typhlocybae*, which is recommended as a biological control agent (Strauss, 2010, Vétek et al., 2019). This species is actively spreading in Europe, in 2022 it was reported from Poland (Świerczewski et al., 2022), but has not yet been registered in Ukraine. MaxEnt modelling has shown that the territory of Ukraine is suitable for the parasitoid, albeit unevenly. There are prospects for the introduction and use of this parasitoid, especially in the south of Ukraine, and this is very useful, because it is in the south that there are favourable conditions for *M. pruinosa* as well. In the context of climate change, the area of favourable areas for the parasitoid is increasing, although there is a certain redistribution of suitability. The following factors play a major role in the spread of the parasitoid: bio 15 (Precipitation Seasonality), bio 6 (Min Temperature of Coldest Month), bio 17 (Precipitation of Driest Quarter).

The best way to minimize damage from invasive species is to prevent their invasion, since it is extremely difficult to eliminate already dispersed species. As a result, many countries are looking for ways to prevent the invasions through initial monitoring. Because geospatial modelling has already been successfully used in many countries and has been widely used to predict the spread of invasive species, these programs can be recommended as an effective tool for preventive monitoring for early detection and rapid response to alien species, as well as for developing models for predicting migration, dispersal and spread of invasive species caused by climate change.

Conclusions

For the first time in Ukraine, the risk of spreading *M. pruinosa* beyond its identified habitats has been identified, which is determined by the presence of a wide range of host plants and climatic conditions that meet the requirements of the species. Existing phytosanitary measures cannot at present reliably prevent the risk of *M. pruinosa* spreading in Ukraine.

The suitability of the territory of Ukraine for *M. pruinosa* and its natural parasitoid *N. typhlocybae* under current and future climatic conditions was determined. The most favourable areas for both species are located in the south, east and centre of the country and in the Zakarpattia Region. There are prospects for the introduction of *N. typhlocybae* for classical biocontrol, especially in the southern regions of Ukraine.

The main bioclimatic factors influencing the distribution of the species are: bio 10 (Mean Temperature of Warmest Quarter), bio 17 (Precipitation of Driest Quarter), bio 6 (Min Temperature of Coldest Month), bio 15 (Precipitation Seasonality).

Other factors such as spread by transport and plant material, availability of host plants and woody plants for overwintering of *M. pruinosa* may influence the distribution of the species.

It is necessary to develop an effective *M. pruinosa* population control system to prevent further spread and reduce the damage caused by the pest. One of the most effective risk management measures may be to include *M. pruinosa* in the list of regulated non-quarantined pests in Ukraine. It is recommended to monitor plantations on the territory of Ukraine for the presence of *M. pruinosa*, as well as to increase public awareness of these pests and the prospects of their biocontrol.

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