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Bioclimatic modeling of the distribution of brown marmorated stink bug *Halyomorpha halys* (Stål, 1855), with special reference to Ukraine

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Due to the potential severity of the impact of brown marmorated stink bug Halyomorpha halys both in terms of the plant susceptibility and economic loss and the border detection of the bug in the seaport city of Odesa, it is important to determine the potential suitable bioclimatic range in Ukraine. The bioclimatic modeling suggests that, under the current climate conditions, the pest has varying chances in the near term to invade a number of regions in Ukraine, especially in the south of the country: Transcarpathia, Crimea, portions of Odesa, Mykolaïv, Kherson, and Zaporizhzhya regions.

Keywords: *Halyomorpha halys, bioclimatic modeling, Ukraine.*

The brown marmorated stink bug *Halyomorpha halys* (Stål, 1855), an invasive species of Pentatomidae (Heteroptera) native to the Eastern Asia, was unintentionally introduced into the United States and Europe in recent years [1]. The species has already appeared in Sochi (Russian Federation) and Georgia and is assumed to have been brought to Sochi from Europe (Italy) with a planting material of ornamental plants for landscaping the XXII Olympic Winter Games [2]. Most recently, in 2016, the bug en masse has been recorded in Odesa (Ukraine) [3].

This phytophagous species is a generalist and has been recorded feeding on nearly 50 families of plants. However, it shows, possibly, a preference for plants in the families Fabaceae and Rosaceae [4] and can damage various field crops, vegetables, tree fruits, and ornamentals.

The diversity of genetic haplotypes in Europe indicates the dispersion of *H. halys* within the continent and the formation of secondary invasion centers, but there is also evidence for recurrent introductions from Asia or the USA [5]. Species distribution modeling (SDM) even suggests that its expansion has just begun, because the models have predicted large areas suitable for *H. halys* in Europe approximately between 40 and 50 °N [6].

The recent spread of successfully established *H. halys* in Europe warrants further such investigations. As good fliers and generalist feeders, this species has the potential to easily disperse

and appear in novel environments. SDM has been used to determine a potential range distribution of the invasive species in new environments. These predictions provide valuable information for the protection of novel environments and the prevention and/or reduction of impacts resulting from invasive species. The potential global invasive range of *H. halys* has previously been mapped [6]. However, due to the potential severity of the impact of this species both in terms of the plant susceptibility and economic loss and the border detection of the bug in the seaport city of Odesa, it is important to determine the potential suitable bioclimatic range in Ukraine. This study aims to highlight the extent of the potential problem and to facilitate a future management of this destructive species in Ukraine.

Materials and Methods. Occurrence data for this species was collected using Global Biodiversity Information Facility [7] and updates of its European distribution [1]. A total of 573 non-duplicate records were considered. To reduce the sampling bias and spatial autocorrelation, some models were generated using all available occurrence points, and the spatial autocorrelation was measured among model pseudo-residuals by calculating Moran's *I* at multiple distance classes using the SAM v4.0 software [8]. Moran's *I* is a widely used measure of spatial autocorrelation, ranging from 0 to 1, with values >0.3 considered relatively large. A minimum distance of 53.9 km, at which Moran's *I* < 0.3 was detected. Next, we used the spThin package in R [9] to subsample our dataset such that all occurrence records were separated by this minimum distance. Thinning resulted in retaining 73 occurrence records. Five SDM methods were employed using the "sdm" package within the statistical software R [10], including "random forests", "boosted regression trees", "bioclim", "maxent" and "support vector machine", and evaluated (using 30 % of the occurrence dataset) by 10-fold cross-validation. The performance of the models was evaluated using the true skill statistics (TSS). The package provides the ensemble forecasting that is relatively robust against the uncertainty in individual models. In the present study, the predictive distribution map of *H. halys* for the current climate resulted from the ensemble forecasting by parameterizing TSS > 0.65 for individual models. Importantly, "sdm" ranks the environmental layers used to train the SDM based on their relative importance in the model formulation and also allows the construction of a response curves to illustrate the effect of selected variables on the predicted occurrence.

For the bioclimatic modeling, we used the CliMond archive, a set of climate data products [11]. Gridded variables in this set are derived from monthly temperature and rainfall values in order to generate biologically meaningful variables representing annual trends, seasonality, and extreme or limiting environmental factors. Predictor variables with a variance inflation factor greater than 10 were excluded from the model fitting to avoid multicollinearity effects. Selected layers (Table 1) were clipped to a bounding box, and a resolution of 10 arcmin was used.

Table 1. **Environmental layers used for the model fitting**

Variable code	Variable
Bio01	Annual mean temperature (°C)
Bio02	Mean diurnal temperature range (°C)
Bio04	Temperature seasonality (CV*)
Bio08	Mean temperature of wettest quarter (°C)
Bio09	Mean temperature of driest quarter (°C)
Bio15	Precipitation seasonality (CV)
Bio18	Precipitation of warmest quarter (mm)
Bio19	Precipitation of coldest quarter (mm)
Bio23	Radiation seasonality (CV)
Bio26	Radiation of warmest quarter ($W \cdot m^{-2}$)
Bio35	Mean moisture index of coldest quarter

*CV — coefficient of variation.
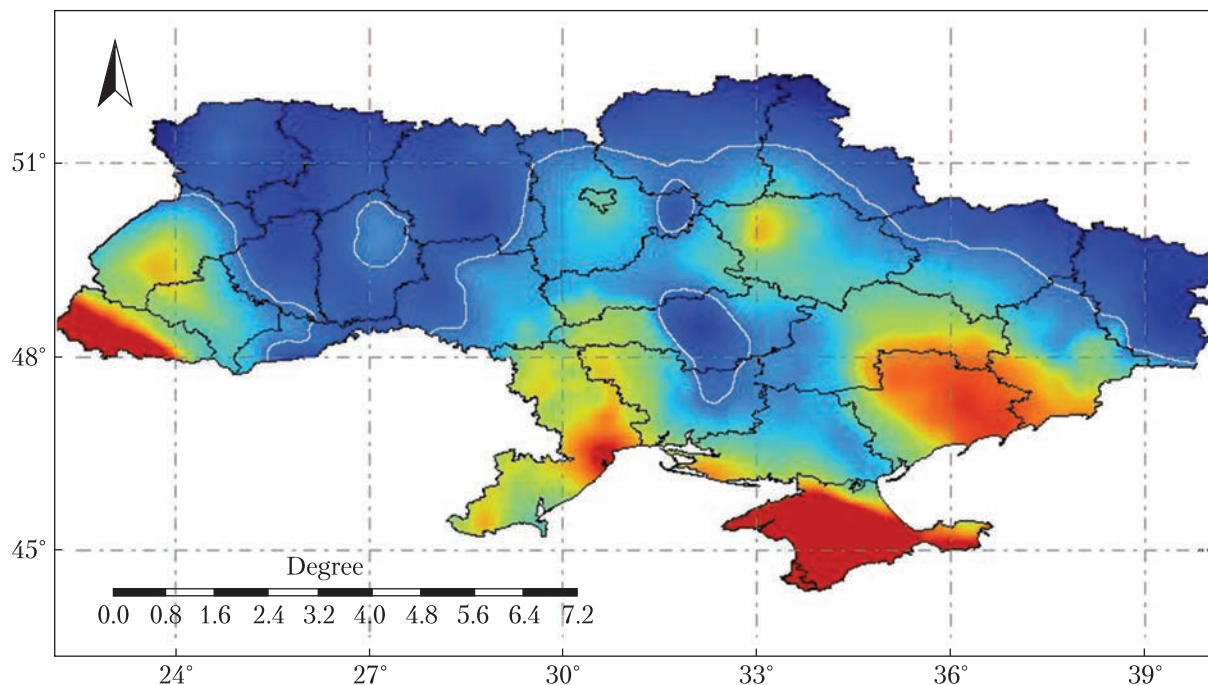
Ensemble map for brown marmorated stink bug *Halyomorpha halys* in Ukraine. Red color indicates the areas of higher bioclimatic suitability, whereas blue indicates the opposite, and the white line represents the accepted threshold

Table 2. **Performance of the employed models**

SDM methods	Random forests	Boosted regression trees	Bioclim	Maxent	Support vector machine
TSS	0.80	0.60	0.34	0.67	0.69

Maps of the habitat suitability in the ASCII format were processed and visualized in SAGA GIS [12].

Results and Discussion. Results of the performance of the employed models are presented in Table 2.

The most accurate technique was "random forests" (TSS = 0.80), and the least accurate was "bioclim" (TSS = 0.34). In terms of the variable importance, Annual mean temperature (Bio01) and Temperature seasonality (Bio04) were the highest contributing variables in the formulation of the models accounting for up to nearly 60 % of the variation. Based on the response curves, the predicted occurrence of the bug rapidly increases from the point when annual mean temperatures reach 8.21 °C, whereas the increasing variation in Temperature seasonality above 0.0268 strongly reduces chances for finding the species. These results are consistent with facts concerning the geographical origin of the bug and reports that *H. halys* is chill-intolerant (i.e., dies before reaching its freezing point) [13]. In this case, the winter season is a critical period for the survival of the species. In natural settings, the bug seeks a shelter beneath loose bark on trees, but aggregations can also occur in human-made structures. Refugia provided by thermally buffered human-

built structures are likely to be crucial for the overwintering survival during atypically cold winters and may contribute to the northern geographic range expansion of this economically damaging insect in the temperate climates [13]. Therefore, it can be expected that *H. halys* can appear in areas, where the predicted occurrence is below an optimum based exclusively on the bioclimate. Under such conditions, there is a need to consider different models to cope with uncertainty and to apply thresholds close to a zero omission error. In our case, a threshold value of 0.1 was considered to be the most relevant to identify suitable and unsuitable areas for the pest.

High-accuracy predictive distribution maps from the "random forests", "maxent", and "support vector machine" models were combined to form the ensemble forecasting of *H. halys*, as shown in Figure.

From the map, it can be seen that *H. halys* under the current climate conditions has varying chances in the near term to invade a number of regions in Ukraine, especially in the south of the country: Transcarpathia, Crimea, portions of Odesa, Mykolaïv, Kherson, and Zaporizhzhya regions. Results of these predictions provide a theoretical reference framework for the management and prevention of the spread of brown marmorated stink bug in Ukraine, which may assist resource managers facing today the challenge of determining where an invasive species outbreak may occur, and where an invasive species will move next.

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БІОКЛІМАТИЧНЕ МОДЕЛЮВАННЯ ПОШИРЕННЯ МАРМУРОВОГО КЛОПА *HALYOMORPHA HALYS* (STÅL, 1855) З ОСОБЛИВИМ ПОСИЛАННЯМ НА УКРАЇНУ

Зважаючи на шкодочинність мармурового клопа *Halyomorpha halys* для сільськогосподарських культур і пов'язані з цим економічні втрати, а також виявлення цього шкідника в портовому місті Одеса, важливо визначити території в Україні, де біокліматичні умови сприятимуть його поширенню. Згідно з результатами біокліматичного моделювання, за сучасних кліматичних умов шкідник має різні шанси в найближчій перспективі вторгнутись у низку регіонів України, особливо на півдні країни: Закарпаття, Крим, частину Одеської, Миколаївської, Херсонської та Запорізької областей.

Ключові слова: *Halyomorpha halys, біокліматичне моделювання, Україна.*

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БИОКЛИМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЯ МРАМОРНОГО КЛОПА *HALYOMORPHA HALYS* (STÅL, 1855) СО СПЕЦИАЛЬНОЙ ССЫЛКОЙ НА УКРАИНУ

Учитывая вредоносность мраморного клопа *Halyomorpha halys* для сельскохозяйственных культур и связанные с этим экономические потери, а также обнаружение этого вредителя в портовом городе Одесса, важно определить территории в Украине, где биоклиматические условия будут способствовать его распространению. Согласно результатам биоклиматического моделирования, в современных климатических условиях вредитель имеет разные шансы в ближайшей перспективе вторгнуться в ряд регионов Украины, особенно на юге страны: Закарпатье, Крым, часть Одесской, Николаевской, Херсонской и Запорожской областей.

Ключевые слова: *Halyomorpha halys, биоклиматическое моделирование, Украина.*