The Asian tiger mosquito, *Aedes (Stegomyia) albopictus* (Skuse, 1895), is a mosquito native to the tropical and subtropical areas of the Southeast Asia. However, in the past few decades, this species has spread to many countries around the globe, largely through the international trade in used tires [1]. *Ae. albopictus* is an important vector for the transmission of many viral pathogens and capable of hosting the Zika virus, it is important to determine the potential suitable bioclimatic range in Ukraine. Bioclimatic modelling suggests that, under current climate conditions, the vector species has varying chances in the near term to invade a number of regions in Ukraine, especially in the south and west of the country: particularly, Crimea, the southern portion of the Odesa region, and Transcarpathian one and, to a less extent, the Precarpathian region. Under the risk of invasion by the mosquito vector, are as well coastal areas of the Black and Azov seas.

**Keywords:** *Aedes albopictus*, bioclimatic modeling, Ukraine.

Due to the spread of *Aedes albopictus* to many countries around the globe, which is an important mosquito vector for the transmission of many viral pathogens and capable of hosting the Zika virus, it is important to determine the potential suitable bioclimatic range in Ukraine. Bioclimatic modelling suggests that, under current climate conditions, the vector species has varying chances in the near term to invade a number of regions in Ukraine, especially in the south and west of the country: particularly, Crimea, the southern portion of the Odesa region, and Transcarpathian one and, to a less extent, the Precarpathian region. Under the risk of invasion by the mosquito vector, are as well coastal areas of the Black and Azov seas.

**Keywords:** *Aedes albopictus*, bioclimatic modeling, Ukraine.
pied suitable habitats and posing a risk to human health in the majority of locations, where
the mosquitoes can survive and reproduce.

*Ae. albopictus* was first reported in Europe in 1979 in Albania. Then the spread has occurred
to a number of countries in Europe, including those neighboring Ukraine. Information collected
from the Black Sea region has already revealed the presence of *Ae. albopictus* in Bulgaria, Romania,
western and north-eastern Turkey, southern Russia and Georgia [5—7].

Exploring the climatic limiting factors may help to understand the key drivers of the sug-
gested range expansion of the species and may, at the same time, help establishing efficient mo-
nitoring programs including risk assessments of *Ae. albopictus*. Our objective was to predict
the possible geographic range of the mosquitoes based on the presence records and climatic va-
riables likely to be associated with the environmental suitability. Thus, findings of this study can
about inform enhanced surveillance efforts in Ukraine, where *Ae. albopictus* has not yet been
recorded, but where the environment appears to be favorable for its establishment.

The basic approach applied here is based on species distribution models (SDMs), often also
called ecological niche models (ENMs), where species’ presences or absences are correlated with
environmental variables prevailing in the respective locations in order to project the potential
distribution of a species under current and/or future climatic conditions. These projections can
be based on many different statistical and/or machine learning algorithms, all aiming at esti-
mating this species-environment-relationship best.

**Materials and Methods.** Occurrence data for this species are collected using the global
compendium of *Ae. albopictus* occurrence [8] are updated [5—7, etc.]. A total of 327 non-dupli-
cate records across Europe were considered. To reduce the sampling, bias and spatial auto-
correlation models were generated using all available occurrence points, and the spatial autocor-
relation was measured among model pseudo-residuals by calculating Moran’s *I* at multiple dis-
tance classes. 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 is equal to 54 km, at which
Moran’s *I* < 0.3 was detected. Next, we used the spThin package in R [9] to subsample our data set
such that all occurrence records were separated by this minimum distance. Thinning resulted in
retaining 156 occurrence records. Five SDM methods were employed using the “sdm” package
within the statistical software R [10], including “random forests”, “boosted regression trees”, “bio-
clim”, “maxlike”, and “support vector machine”, and evaluated (using 30 % of the occurrence
data set) by a bootstrapping procedure. The performance of the models was evaluated using the
true skill statistic (TSS). The package also provides the ensemble forecasting that is relatively
robust against the uncertainty in individual models. In the present study, the predictive distrib-
bution map of *Ae. albopictus* for the current climate resulted from the ensemble forecasting using
the weighted averaging based on the TSS statistic 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 response curves to illustrate the effect of
selected variables on the predicted occurrence.

For modeling, we used a recently reconsidered (in terms of biological significance) set of
16 climatic and two topographic variables, the ENVIREM data set [11], many of which are likely
to have direct relevance to ecological or physiological processes determining the species distri-
butions. Predictor variables with a variance inflation factor (VIF) 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 5 arcmin was used.

Maps of habitat suitability in the ASCII format were processed and visualized in GIS software.

**Results and Discussion.** Results of the performance of the employed models are presented in Table 2. The most accurate technique was “random forests” (TSS = 0.81) and the least accurate was “bioclim” (TSS = 0.43).

In terms of variable importance, embergerQ, minTempWarmest, and PETColdestQuarter were the highest contributing variables in the formulation of the models, 20.6, 19.1, and 17.7 %, respectively, and together accounted for 57.4 % of the total variation. Based on the response curves, the predicted habitat suitability enhancing the mosquito occurrence rapidly increases at higher values of the embergerQ, which characterizes the dryness of a climate in terms of the mean maximum temperature of the warmest month, the mean minimum temperature of the coldest month, and the mean annual precipitation. Values of embergerQ are especially low, when the climate is dry. Such a response is consistent with expectations, since the species needs small aquatic habitats for egg deposition and breeding places. An annual precipitation of at least 500 mm has been proposed, which ensures the maintenance of breeding places [12]. Similarly, the habitat suitability is enhanced by higher values of the minTempWarmest reflecting the species’ adaptation to higher temperatures [13]. Finally, PETColdestQuarter, an ecologically important aspect of the climate linked to the energy supply [14], reduces the habitat suitability at

| Variable abbreviation | Brief description | Units |
|-----------------------|------------------|-------|
| aridityIndexThornthwaite | Thornthwaite aridity index: Index of the degree of water deficit below water need | — |
| continentality | Average temperature of warmest month minus average temperature of coldest month. | °C |
| embergerQ | Emberger’s pluviothermic quotient | — |
| minTempWarmest | Minimum temperature of the warmest month | °C · 10 months |
| monthCountByTemp10 | Count of the number of months with mean temp greater than 10 °C | months |
| PETColdestQuarter | Mean monthly PET* of coldest quarter | mm/month |
| PETDriestQuarter | Mean monthly PET of driest quarter | mm/month |
| PETWarmestQuarter | Mean monthly PET of warmest quarter | mm/month |
| PETWettestQuarter | Mean monthly PET of wettest quarter | mm/month |
| topowet | SAGA-GIS topographic wetness index | — |

*Potential evapotranspiration.

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

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

| SDM methods | Random forests | Boosted regression trees | Bioclim | Maxlike | Support vector machine |
|-------------|----------------|--------------------------|---------|---------|-----------------------|
| TSS | 0.81 | 0.61 | 0.43 | 0.58 | 0.68 |
These results are consistent with facts concerning the geographical origin of *Ae. Albopictus*. In this case, the winter season is a critical period for the survival of the species. However, there are suggestions that this species may have adapted to indoor environments [15]. Refugia provided by thermally buffered human-built structures are likely to be crucial for overwintering survival during cold winters and may contribute to the northern geographic range expansion of this epidemiologically important vector in temperate climates. Therefore, *Ae. Albopictus* could probably appear in areas, where the predicted habitat suitability is below an optimum based exclusively on the bioclimate. Under such circumstances, 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 0.2 was arbitrarily considered to be the most relevant to identify suitable and unsuitable areas for the vector. High-accuracy predictive distribution maps from the “random forests”, “boosted regression trees”, “maxlike” and “support vector machine” models were combined to form ensemble forecasting of the distribution of *Ae. Albopictus* in Ukraine, as shown in Figure.

From the map, it can be seen that *Ae. Albopictus* under current climate conditions has varying chances in the near term to invade a number of regions in Ukraine in the south and west of the country, particularly Crimea, the southern portion of Odesa region, Transcarpathian region and, to a less, extent, the Precarpathian region. Under the risk of invasion by the vector are as well...
coastal areas along the Black and Azov seas, where seaside holiday resorts in the summer host up to 10—12 and 7 million people a year, respectively.

Results of these predictions provide a theoretical reference framework for the prevention of the spread of the Asian tiger mosquito in Ukraine and may help establishing the efficient monitoring programs including risk assessments of the vector and elucidating the consequences for public health.

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**БІОКЛІМАТИЧНЕ МОДЕЛЮВАННЯ ЄВРОПЕЙСЬКОГО ПОШИРЕННЯ ІНВАЗИВНОГО АЗІЙСЬКОГО КОМАРА *AEDES (STEGOMYIA) ALBOPICTUS* (SKUSE, 1895) З ОСОБЛИВИМ ПОСИЛАННЯМ НА УКРАЇНУ**

Через поширення у багатьох країнах світу комарів виду *Aedes albopictus*, який є переносником низки вірусних збудників хвороб людини, у тому числі вірусу Зіка, є нагальна потреба визначити його потенційний біокліматичний ареал в Україні. На підставі результатів біокліматичного моделювання можна припустити, що за сучасних кліматичних умов цей переносник має різний шанс найближчим часом поширитися у низку регіонів України, особливо на північні та західні країни: зокрема, Крим, південно-західну частину Одеської області та Закарпаття і меншою мірою Прикарпаття. Під загрозою інвазії з боку цього виду також знаходяться прибережні райони уздовж Чорного та Азовського морів.

**Ключові слова:** *Aedes albopictus*, біокліматичне моделювання, Україна.

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**БИОКЛИМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ЕВРОПЕЙСКОГО РАСПРОСТРАНЕНИЯ ИНВАЗИВНОГО АЗИАТСКОГО КОМАРА *AEDES (STEGOMYIA) ALBOPICTUS* (SKUSE, 1895) СО СПЕЦИАЛЬНОЙ ССЫЛКОЙ НА УКРАИНУ**

Из-за распространения во многих странах мира комаров вида *Aedes albopictus*, который является переносчиком ряда вирусных возбудителей болезней человека, в том числе вируса Зика, необходимо определить его потенциальный биокліматический ареал в Украине. На основании результатов биоклиматического моделирования можно предположить, что в современных климатических условиях этот переносчик имеет разные шансы в ближайшее время распространиться в ряд регионов Украины, особенно на юге и западе страны: в частности, Крым, южную часть Одесской области и Закарпатья, и в меньшей степени Прикарпатье. Под угрозой инвазии со стороны этого вида также находятся прибрежные районы Черного и Азовского морей.

**Ключевые слова:** *Aedes albopictus*, биоклиматическое моделирование, Украина.