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I.I Kozynenko, V.M. Tytar

НТУ України “Київський політехнічний інститут”
E-mail: dfhggh

Bioclimatic modeling of the European distribution of the invasive Asian tiger mosquito, *Aedes* (*Stegomyia*) *albopictus* (Skuse, 1895), with special reference to Ukraine

Presented by Corresponding Member of the NAS of Ukraine I.A. Akimov

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, the coastal areas of the Black and Azov seas are.

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

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, including the yellow fever virus, dengue fever, and Chikungunya fever [2], as well as several filarial nematodes. *Ae. albopictus* is considered as a potential vector for the Zika transmission among the humans [3]. The spread of these diseases has become a major global health concern, and it is predicted that a climate change will affect the mosquitoes' distribution, which will allow these insects to bring new pathogens to unaffected populations [4]. The predicted expansion of this species is considered to be driven primarily by environmental changes that create new habitats, including changes in the climate, especially the temperature. Even under current climate conditions and population densities, the species will continue to spread, filling unoccu-

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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 suggested range expansion of the species and may, at the same time, help establishing efficient monitoring 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 variables 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 estimating this species-environment-relationship best.

Materials and Methods. Occurrence data for this species are collected using the global compendium of *Ae. albopictus* occurrence [8] and are updates [5—7, etc.]. A total of 327 non-duplicate records across Europe were considered. To reduce the sampling, bias and spatial autocorrelation 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. 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", "bioclim", "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 distribution 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 distributions. 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 the 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 a small aquatic habitats for the 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

***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

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

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
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.

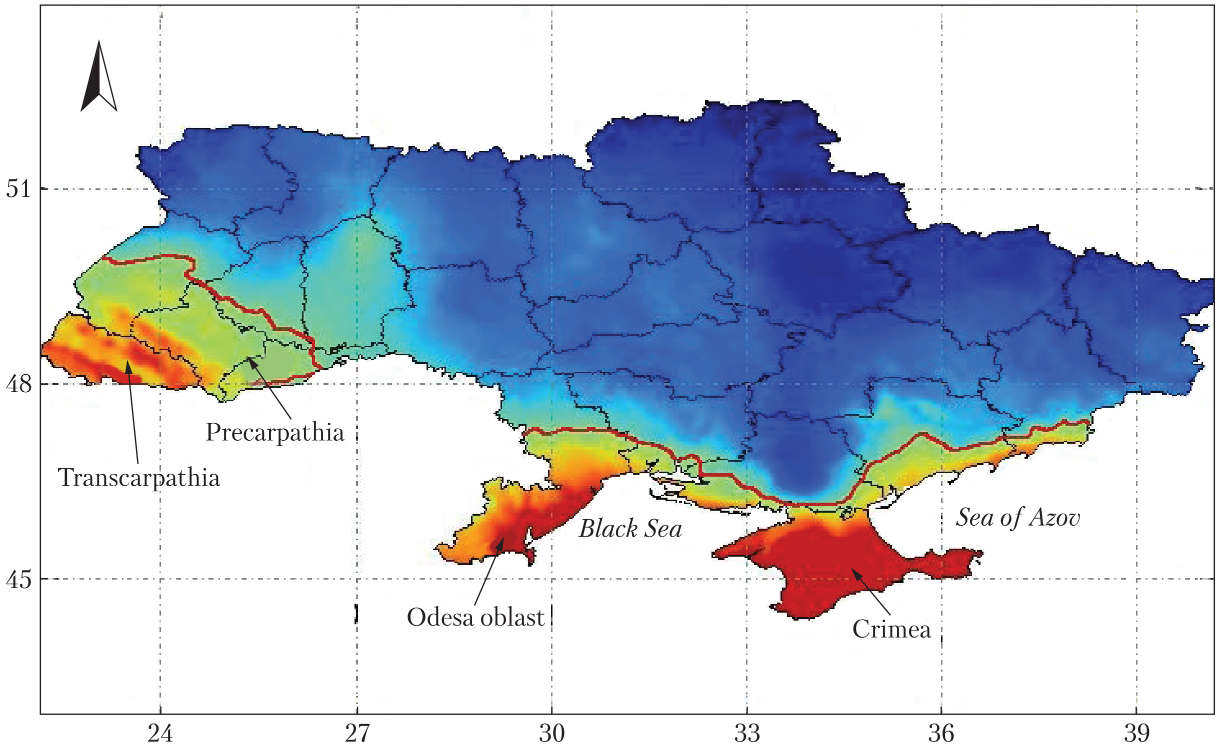

Fig. Ensemble map for the predicted distribution of the Asian tiger mosquito, *Aedes albopictus,* in Ukraine. Red color indicates areas of higher bioclimatic suitability, whereas blue indicates the opposite; the red line represents the accepted threshold

low levels, emphasizing the importance of winter conditions for the establishment of the species in a non-native range.

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.

REFERENCES

1. Benedict, M. Q., Levine, R. S., Hawley, W. A. & Lounibos, L. P. (2007). Spread of the tiger: global risk of invasion by the mosquito *Aedes albopictus*. Vector Borne Zoonotic Dis., 7, No. 1, pp. 76-85. https://doi.org/10.1089/vbz.2006.0562
2. Hochedez, P., Jaureguiberry, S., Debruyne, M., Bossi, P., Hausfater, P., Brucker, G., Bricaire, F. & Caumes, E. (2006). Chikungunya infection in travelers. Emerg. Infect. Dis., 12, No. 10, pp. 1565-7. https://doi.org/10.3201/eid1210.060495
3. Grard, G. Caron, M., Mombo, I. M., Nkoghe, D., Ondo, S. M., Jiolle, D., Fontenille, D., Paupy, C., Leroy, E. M. (2014). Zika Virus in Gabon (Central Africa) – 2007: A new threat from *Aedes albopictus*? PLOS Negl. Trop. Dis., 8, No. 2, e2681. https://doi.org/10.1371/journal.pntd.0002681
4. Reinhold, J. M., Lazzari, C. R. & Lahond re, C. (2018). Effects of the environmental temperature on *Aedes aegypti* and *Aedes albopictus* mosquitoes: a review. Insects, 9, No. 4, pii: E 158. https://doi.org/10.3390/insects9040158
5. Akiner, M. M., Demirci, B., Babuadze, G., Robert, V. & Schaffner, F. (2016). Spread of the invasive mosquitoes *Aedes aegypti* and *Aedes albopictus* in the Black Sea Region increases risk of Chikungunya, Dengue, and Zika outbreaks in Europe. PLoS Negl. Trop. Dis., 10, No. 4, e0004664. https://doi.org/10.1371/journal.pntd.0004664
6. Kutateladze, T., Zangaladze, E., Dolidze, N., Mamatsashvili, T., Tskhvaradze, L., Andrews, E. S. & Haddow, A. D. (2016). First record of *Aedes albopictus* in Georgia and updated checklist of reported species. J. Am. Mosq. Control. Assoc., 32, No. 3, pp. 230-233. https://doi.org/10.2987/16-6574.1
7. Fedorova, M. V., Shvets, O. G., Yunicheva, Y. V., Medyanik, I. M., Ryabova, T. E. & Otstavnova, A. D. (2018). Dissemination of invasive mosquito species, *Aedes* (*Stegomyia*) *aegypti* (L., 1762) and *Aedes* (*Stegomyia*) *albopictus* (Skuse, 1895) in the south of Krasnodar Region, Russia. Problems of Particularly Dangerous Infections, 2, pp. 101-105. https://doi.org/10.21055/0370-1069-2018-2-101-105 (in Russian).
8. Kraemer, M. U., Sinka, M. E., Duda, K. A., Mylne, A., Shearer, F. M., Brady, O. J., Messina, J. P., Barker, C. M., Moore, C. G., Carvalho, R. G., Coelho, G. E., Van Bortel, W., Hendrickx, G., Schaffner, F., Wint, G. R., Elyazar, I. R., Teng, H. J. & Hay, S. I. (2015). The global compendium of *Aedes aegypti* and *Ae. albopictus* occurrence. Sci. Data, 2, 150035. https://doi.org/10.1038/sdata.2015.35
9. Aiello-Lammens, M. E., Boria, R. A., Radosavljevic, A., Vilela, B. & Anderson, R. P. (2015). spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models. Ecography, 38, No. 5, pp. 541-545. https://doi.org/10.1111/ecog.01132
10. Naimi, B. & Araújo, M. B. (2016). sdm: a reproducible and extensible R platform for species distribution modelling. Ecography, 39, No. 4, pp. 368-375. https://doi.org/10.1111/ecog.01881
11. Title, P. O. & Bemmels, J. B. (2018). ENVIREM: an expanded set of bioclimatic and topographic variables increases flexibility and improves performance of ecological niche modeling. Ecography, 41, No. 2, pp. 291-307. https://doi.org/10.1111/ecog.02880
12. Caminade, C., Medlock, J. M., Ducheyne, E., McIntyre, K. M., Leach, S., Matthew, B. & Morse A. P. (2012). Suitability of European climate for the Asian tiger mosquito *Aedes albopictus*: recent trends and future scenarios. J. R. Soc. Interface, 9, Iss. 75, pp. 2708-2717. https://doi.org/10.1098/rsif.2012.0138
13. Alto, B. W. & Juliano S. A. (2001). Temperature effects on the dynamics of *Aedes albopictus* (*Diptera*: *Culicidae*) populations in the laboratory. J. Med. Entomol., 38, No. 4, pp. 548-556. https://doi.org/10.1603/0022-2585-38.4.548
14. O'Brien, E. M. (2006). Biological relativity to water–energy dynamics. J. Biogeogr., 33, Iss. 11, pp. 1868-1888. https://doi.org/10.1111/j.1365-2699.2006.01534.x

15. Dieng, H., Saifur, R. G., Hassan, A. A., Salmah, M. R., Boots, M., Satho, T., Jaal, Z. & AbuBakar, S. (2010). Indoor-breeding of *Aedes albopictus* in northern peninsular Malaysia and its potential epidemiological implications. PloS One, 5, No. 7, e11790. https://doi.org/10.1371/journal.pone.0011790

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І.І. Козиненко, В.М. Титар
Інститут зоології ім. І.І. Шмальгаузена НАН України, Київ
E-mail: kozinenko@gmail.com, vtytar@gmail.com

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 півдні та заході країни: зокрема, Крим, південну 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.*

И.И. Козиненко, В.М. Титар
Институт зоологии им. И.И. Шмальгаузена НАН Украины, Киев
E-mail: vtytar@gmail.com, kozinenko@gmail.com

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 биоклиматический 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 Прикарпатья. Под угрозой инвазии со стороны этого вида также находятся прибрежные районы Черного и Азовского морей.

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