Ticks and Tick-borne Diseases 14 (2023) 102102

Contents lists available at ScienceDirect

Ticks and Tick-borne Diseases

journal homepage: www.elsevier.com/locate/ttbdis

Original article

Tick maps on the virtual globe: First results using the example of *Dermacentor reticulatus*

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ARTICLE INFO

Keywords:
Google Earth
Species distribution
Model
Random forest

ABSTRACT

Digital maps, particularly displayed on virtual globes, will represent the most important source of geographical knowledge in the future. The best known of these virtual globes is Google Earth, whose use in teaching at schools and universities is now common practice. As the first result of a series of forthcoming digital tick maps, the worldwide distribution of the marsh tick *Dermacentor reticulatus* is shown on Google Earth. For this purpose, various distribution maps of *D. reticulatus* were compiled, including digitized expert maps and a map of suitable habitats compiled with a species distribution model (SDM). A random forest model that estimates suitable habitats by combining information from tick observations, bioclimatic variables, altitude, and land cover was chosen for the latter. In the Google Earth application, the following maps can be selected: a historical expert map, a current expert map, a SDM predicted habitat suitability map, a combined expert-habitat suitability map (considered to be the best representation of the current distribution of *D. reticulatus*), and a map of rasterized tick locations. Users can overlay these maps according to their own requirements or combine it with other Google Earth content. For example, a comparison of the historical with the current expert map shows the spread of *D. reticulatus* over the past few decades. Additionally, high-resolution city maps of Bilbao (Spain), Grenoble (France), Berlin (Germany), Wrocław (Poland), Budapest (Hungary), Bucharest (Romania), and Tomsk (Russia) demonstrate the urban distribution of *D. reticulatus* in public parks, fallow land, and recreational areas. The Google Earth application, developed using the Keyhole Markup Language (KML), also contains fact sheets on biology, ecology, seasonal activity, and vector competence of *D. reticulatus*. This information has been prepared in a compact and easily understandable way for the target group, i.e. scientists from various disciplines, students, and lay people interested in the geographical distribution of ticks.

1. Introduction

The geographical distribution or range of tick species is of major interest and a key aspect especially for surveillance and risk assessment for both human and animals affected by tick-borne diseases such as tick-borne encephalitis, Lyme borreliosis, or rickettsiosis (Eisen and Paddock, 2021). In addition to determining the geographical distribution of tick species, the question also arises of how this knowledge can be made accessible to experts from various scientific disciplines, but also to the public, in a modern way. Classic analogue maps and atlases are increasingly being replaced by digital maps and it can be assumed that these will represent the most important geographic source of knowledge in the future.

The only correct and undistorted representation of our planet and thus the geographical distribution of a tick species on it is the globe. While classic globes are static and therefore only show a single map, digital globes are dynamic and can display and overlay different maps or animate chronological sequence of maps. They can also be used to navigate two- or three-dimensional maps, measure distances, and view user-generated data and photos in the context of the geographic information being displayed. Instead of a fixed scale, as already discussed by Korenberg (1971) for conventional tick maps, the resolution of a zoomable map must be selected. The best known of these digital globes is the virtual globe Google Earth (https://earth.google.com), whose use in teaching at schools and universities is now common practice. Even more advanced technologies such as hologlobes (holograms of earth

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https://doi.org/10.1016/j.ttbdis.2022.102102
Received 18 July 2022; Received in revised form 1 November 2022; Accepted 3 December 2022
Available online 5 December 2022

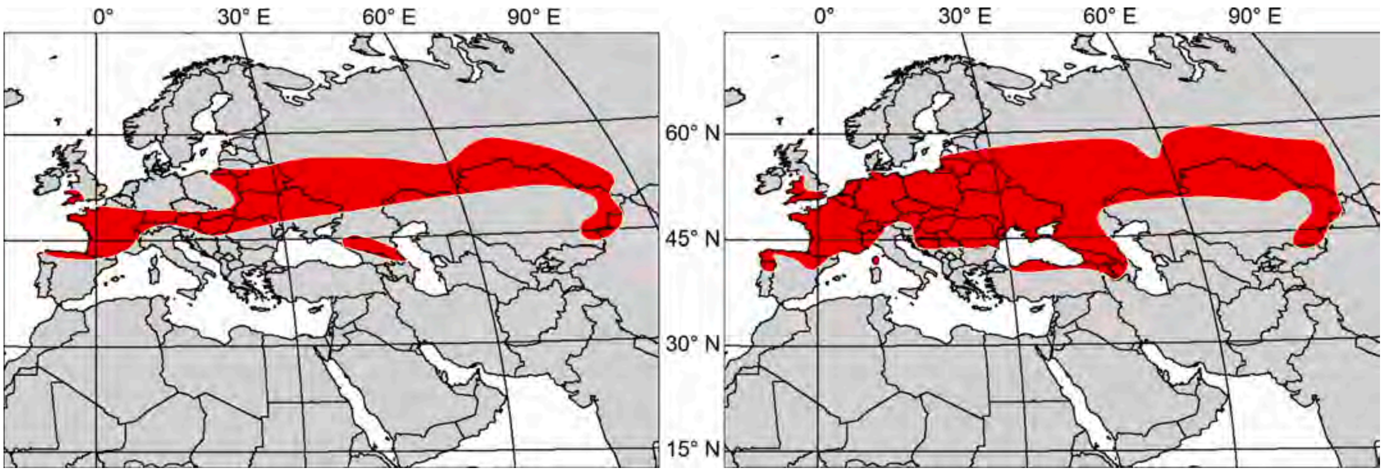

Fig. 1. Global distribution of *Dermacentor reticulatus*: Expert map according to Kolonin (2009) depicting the historical distribution (left) and expert map, hand drawn and digitized by the authors, depicting the current distribution (right).

globes) and tactile hyperglobes are currently in the process of revolutionizing the representation of geographic content. The latter ones are digital globes which show their cartographic image on a real, physical globe body (Buchroithner and Knust, 2013). They are being shown occasionally in technology exhibitions, and are already being used in museums. In general, their technical development is not yet complete and adequate maps are still lacking for many subject areas. This also applies to the virtual globe Google Earth, which is considered here.

While maps depicting global real-time weather conditions, ocean surface current, and temperatures (Beccario, 2021), national weather prediction (National Oceanic and Atmospheric Administration, 2021), global ice and snow coverage (National Snow and Ice Data Center, 2021), climate classification (Rubel et al., 2017), or various other environmental and population parameters are provided on digital globes, the authors are not aware of any maps that show the geographic distribution of ticks. A species distribution map is understood here to be a map that clearly delimits the range of occurrence of a species by means of a contour line or a coloured raster area. Examples of this are the hand-drawn maps in the *Fauna of Ixodid Ticks of the World* (Kolonin, 2009) or the overview maps of the global distribution of *Ixodes ricinus* species complex vectors of Lyme borrelia (Stanek et al., 2012). The creation of a distribution map by experts was demonstrated, for example, by Mihalca et al. (2015) using the locations of the Crimean-Congo haemorrhagic fever vector *Rhipicephalus rossicus*. For this purpose, a contour line was drawn to delimit the distribution around the findings of *R. rossicus*, excluding accidental findings. Although tick findings shown as points on a map also indicate the geographical distribution, they are only an intermediate step in determining the distribution of tick species. In this sense, point maps are not considered here as final distribution maps. A representation of such individual tick locations on Google Earth was, for example, generated for Belgium (Obsomer et al., 2013).

In addition to the classic creation of tick distribution maps by experts, statistical models are used more and more frequently to compile distribution maps. These species distribution models (SDMs) have been calculated for a large number of tick species since the early 2000s. With a view to the genus *Dermacentor* in Europe, SDMs for the sheep tick *D. marginatus* were presented for Spain (Estrada-Peña et al., 2004), Portugal (Estrada-Peña and Santos-Silva, 2005), Italy (Torina et al., 2009), and Germany (Walter et al., 2016), but also for various other regions such as the Mediterranean countries (Estrada-Peña and Venzal, 2007a; 2007b) or China (Yang et al., 2021). For the second *Dermacentor* species endemic in Europe, the marsh tick *D. reticulatus*, SDMs were only recently presented. However, these maps presented by Cunze et al. (2022) do not reflect the currently known distribution of *D. reticulatus*, since no ticks were found in modelled suitable habitats such as in Southern Scandinavia (Kjær et al., 2019). Whether this discrepancy is due to the SDM or to the field study cannot be answered conclusively. On the one hand, the study of Kjær et al. (2019) has its weaknesses in timing the flagging of adult *D. reticulatus* from the vegetation and flagging juvenile *D. reticulatus* as they are mainly found on rodents (Dwuznik-Szarek et al., 2021). On the other hand, the model of Cunze et al. (2022) also failed in the European part of Russia, where it only predicts *D. reticulatus* in the future, although it has been documented there for a long time (Kulik and Vinokurova, 1983).

In this study, special attention is paid to the correct compilation of distribution maps and their representation in Google Earth. Using the example of *D. reticulatus*, it is demonstrated what such distribution maps could look like. *Dermacentor reticulatus* with junior synonym *D. pictus* is known as ornate dog tick or marsh tick in Western Europe and meadow tick in the north-eastern distribution area. It was selected as a suitable tick species because the authors themselves compiled an extensive data set that covers the entire distribution area (Rubel et al., 2020). Accordingly, the distribution area is within the geographic range of -9–88° E/39–60° N. The tick locations in Europe were mapped for the first time by Estrada-Peña et al. (2013) and Rubel et al. (2016), where the three-host tick *D. reticulatus* prefers warm temperate climates with precipitation all year round. In Russia and other countries of the former Soviet Union, the tick locations were mapped for the first time by Kulik and Vinokurova (1983). There, the tick species is found in boreal climates with precipitation all year round and warm summers (Rubel et al., 2020). *Dermacentor reticulatus* is one of 13 known *Dermacentor* species in the Palearctic (Guglielmone et al., 2014). It is rather abundant in some regions and known as the vector of Palma virus, Omsk haemorragic fever virus, tick-borne encephalitis virus, *Anaplasma marginale, Coxiella burnetii, Rickettsia raoultii, R. slovaca, R. sibirica, Babesia caballi*, and *B. canis* (Rubel et al., 2020).

2. Materials and methods

Recently presented *D. reticulatus* locations from the entire distribution area between the Atlantic coast of Portugal and Western Siberia are used (Rubel et al., 2020). This dataset includes 2188 tick locations that were published in the period 1969–2020. Although the covered period ranges over about 50 years, more than the half of the sampling locations was published in the last 10 years. As already discussed above, it is necessary to cover the distribution area as completely as possible with observations in order to obtain a reliable distribution map, regardless of whether it was created manually or calculated with a SDM. Therefore, a further 745 tick locations were considered for this study, which close

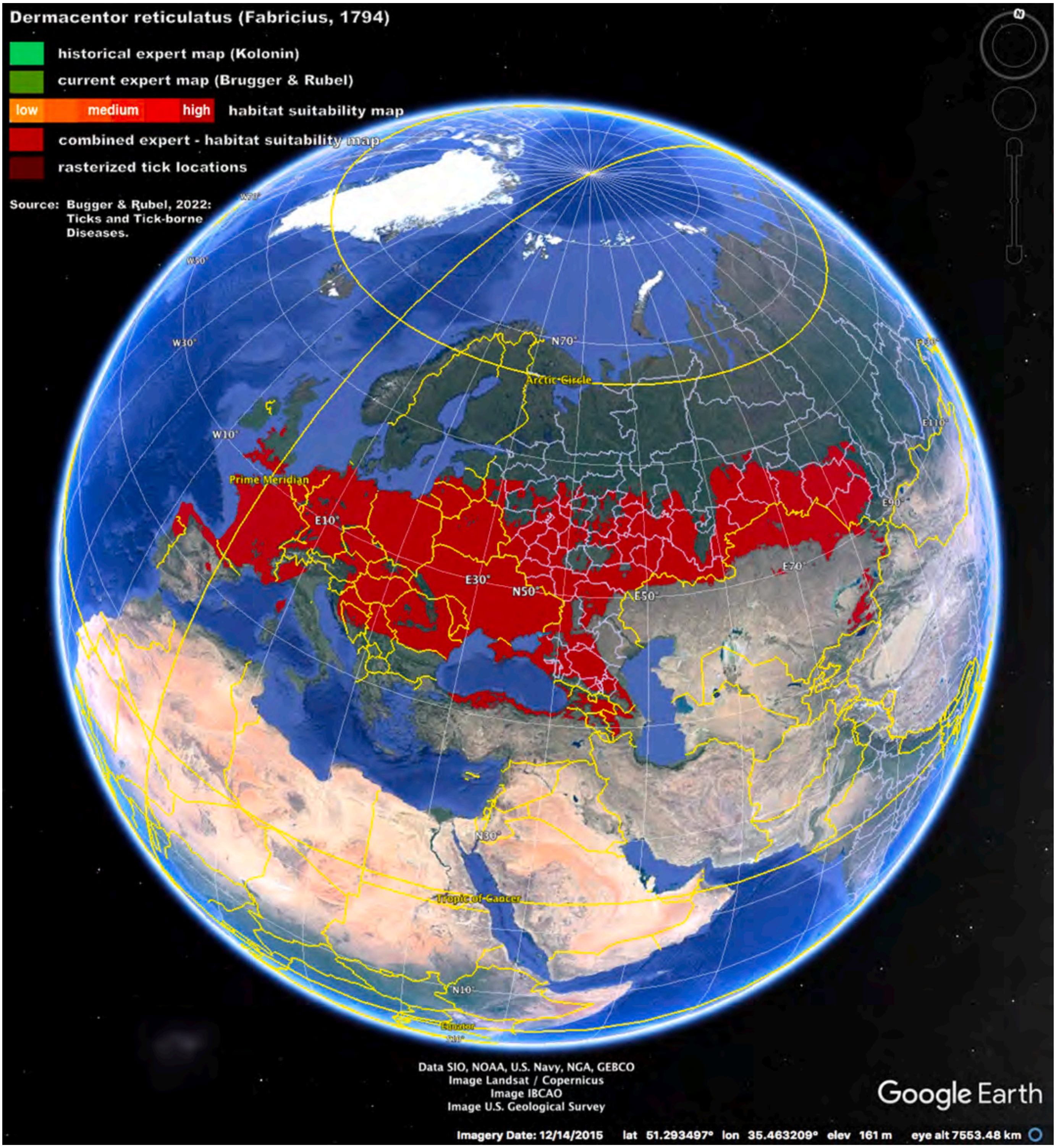

Fig. 2. Global distribution of *Dermacentor reticulatus*: Final map showing suitable tick habitats within the range of the current expert map (combined expert-habitat suitability map).

essential data gaps in the representation of the distribution of *D. reticulatus*. These tick locations are described in the following publications: 25 (Gilot et al., 1973), 1 (Gilot et al., 1976), 1 (Dobler et al., 2008), 1 (Bursali et al., 2013), 13 (Król et al., 2015), 14 (Medlock et al., 2017), 314 (Nebogatkin, 2018), 35 (Sayakova et al., 2019), 66 (Fedoniuk and Podobivsky, 2020), 4 (Kormilitsyna et al., 2020), 2 (Orkun and Emir, 2020), 11 (Silaghi et al., 2020), 25 (Vasilevich and Nikanorova, 2020), 2 (Bellato et al., 2021), 215 (Dwuznik-Szarek et al., 2021), 1 (Garcia-Vozmediano et al., 2021), 7 (Zając et al., 2021), and 8 (Rubel et al., 2022).

The georeferenced *D. reticulatus* locations have different accuracy, classified into high (±0.1 km), medium (±1 km), and low accuracy (±10 km). While all data may be used for the global mapping, only high-precision data can of course be used for city maps. In addition, all reported tick findings were checked for reliability. The data collection of Zhang et al. (2019) going back to 1954 lists 29 *D. reticulatus* locations in

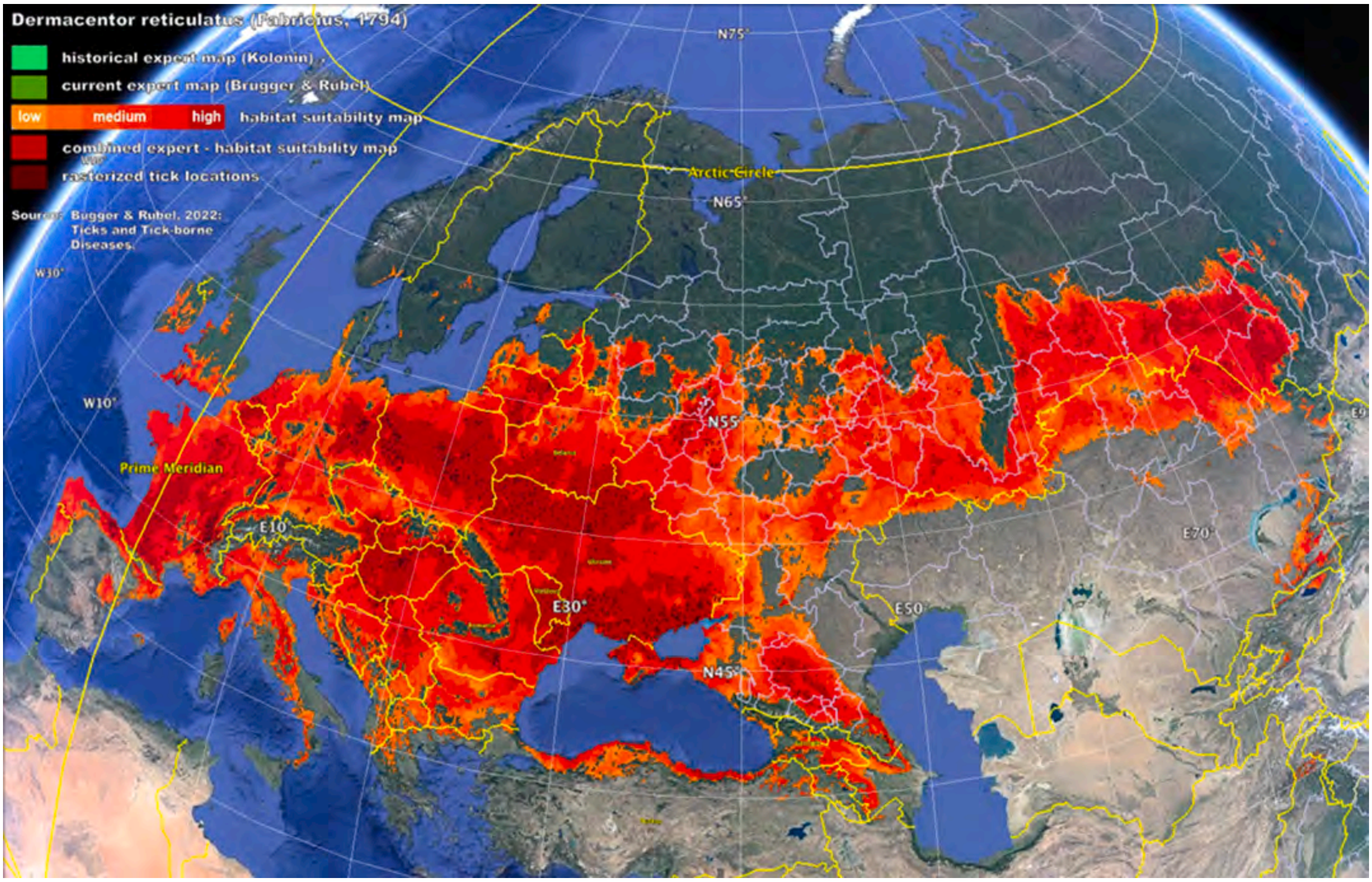

Fig. 3. Global distribution of *Dermacentor reticulatus*: Habitat suitability index > 0.5 (orange to red) predicted with the Random Forest model. Overlayed observations depicted by brown squares. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Chinese province Shaanxi. Since these sites are more than 2000 km away from the nearest endemic area in Kazakhstan and are also in a climatic region unsuitable for *D. reticulatus*, they were not used here. Further, a total of five remote sites from the dataset of Kulik and Vinokurova (1983) were removed as part of the reliability check. Two of them were marked by the authors themselves as lying outside the common range of *D. reticulatus*. At three sites in Uzbekistan *D. reticulatus* seems to have been confused with the common species *Dermacentor marginatus* (Rubel et al., 2020).

One of the first maps of the global distribution of *D. reticulatus* was hand-drawn in the 1980s and last published by Kolonin (2009). It has been digitized, serves as historical background information and is referred to below as the historical expert map. A current expert map was compiled for comparison using the dataset of 2933 tick locations described above. Like the historical expert map, the current expert map was hand-drawn and digitized by the authors. Both expert maps were rasterized with the R language and environment for statistical computing (R Core Team, 2020) and integrated in a Keyhole Markup Language (KML) file (Wernecke, 2009). This is a standard of the Open Geospatial Consortium (https://www.opengeospatial.org/standards/kml) and allows the maps to be accessed in virtual globes such as Google Earth.

As a third map, the habitat suitability of *D. reticulatus* was calculated with a SDM. In the last few decades a large number of different SDMs have been developed, most of which indicate the distribution of a species with a habitat suitability index (Elith et al., 2006; Kessler et al., 2019). What they all have in common is that they are methodologically objective, but it is up to the modeller's subjective skill to select the most suitable input data and to adequately calibrate the model. They are generally more detailed than the classic hand-drawn maps by experts. The technical details have already been discussed elsewhere (Cutler et al., 2007; Phillips et al., 2006). Suitable habitats are estimated by combining information from tick observations and environmental variables. For the latter bioclimatic variables, altitude (height above sea level), and land cover were selected to be representative of the regional to continental scale of the map (Boehnke et al., 2015; Brugger et al., 2016). The bioclimatic variables and the altitude were taken from the WorldClim database version 2.1 (Fick and Hijmans, 2017). The land cover classification was taken from the GlobCover V2.3 dataset of the European Space Agency (2010). To avoid multicollinearity, correlation coefficients were calculated between each pair of predictor variables. A threshold correlation of $|r| < 0.7$ was applied to select a set of low correlated environmental variables (Dormann et al., 2013). One of the machine-learning algorithms, namely the random forests (RF) model (Breiman, 2001), outperforms for species presence in unsampled areas compared to other species distribution models (Walter et al., 2018). Here, we implemented this RF model approach to estimate and depict the habitat suitability, i.e. the probability of presence, for *D. reticulatus* in its entire range in Eurasia. Technically, this means that a raster field of the probability of presence was created in the range from 0 to 1, which can be displayed on the digital globe as a map. A spatial resolution of 5 arc seconds (corresponding to a raster size of about 55 km^2) was chosen. By applying a cut-off threshold on the continuous probability of presence, a species present or not present classification was derived. Mostly the classical threshold of 0.5 is assumed for RF models (Breiman, 2001). Here, this threshold corresponds to the sensitivity-specificity sum maximization approach, also known as Youden Index (Liu et al., 2005). Thus, a value greater than the cut-off threshold implies that *D. reticulatus* is assumed to be present in a given raster cell. A detailed description of the model implementation including variable selection and calibration

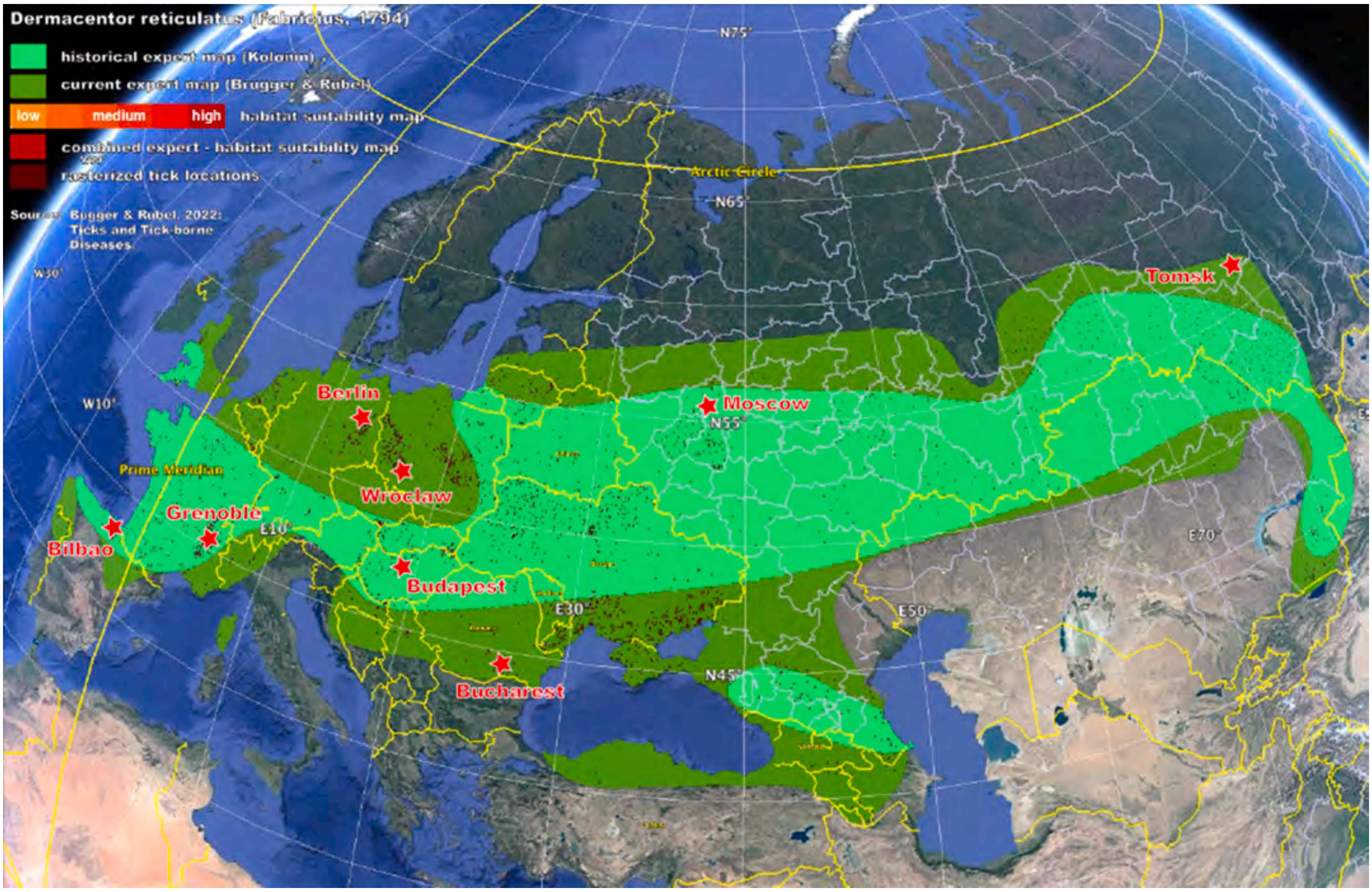

Fig. 4. Global distribution of *Dermacentor reticulatus*: Comparison of historical (light green) and current (dark green) expert maps, hand drawn and digitized by the authors. Overlayed observations depicted by brown squares and locations of the eight city maps marked in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

process is provided in supplement S1.

Since the distribution area determined with the SDM also identifies areas with suitable habitats for which no *D. reticulatus* locations are available, a combination of the habitat suitability map and the current expert map was compiled as a fourth map. In this combined expert-habitat suitability map, the tick distribution estimated with the SDM is limited to the area shown on the current expert map and should come as close as possible to the actual distribution of *D. reticulatus*. The four distribution maps described as well as a map of the rasterized tick locations are made available as digital files (supplement S2).

In recent years, studies of *D. reticulatus* abundance and related tick-borne diseases in cities have grown in importance (Didyk et al., 2017; Grochowska et al., 2021; Hauck et al., 2020; Kovačević et al., 2020; Vogelgesang et al., 2020). In order to show the distribution of *D. reticulatus* in cities and their surroundings, detailed maps of eight selected cities between Bilbao (Spain) and Tomsk (Russia), were compiled. These city maps and a brief description of the distribution, the biology, as well as the medical and veterinary importance of *D. reticulatus* are intended to make the Google Earth application interesting for scientists of various disciplines.

3. Results and discussion

The two hand-drawn expert maps of the distribution of *D. reticulatus* are depicted in Fig. 1. A first visual comparison of the historical map from the 1980s and the current map from 2022 shows a significant increase in the documented distribution area of *D. reticulatus* over the past four decades. In the following, the Google Earth visualization of these two as well as the other *D. reticulatus* distribution maps is presented.

Fig. 2 shows the main result of this study, namely the new distribution map of *D. reticulatus*. It is the combined expert-habitat suitability map, which combines the continental-scale distribution of the observed tick locations with the more detailed prediction of habitat suitability. A KMZ file (S2 supplement) is provided to users to view various maps in the free Google Earth application. As can be seen from the legend in Fig. 2, the following maps can be selected: a historical expert map (light green), a current expert map (dark green), a SDM predicted habitat suitability map (orange to red), a combined expert-habitat suitability map (dark red), and a map of rasterized tick locations (brown). Additionally, eight high-resolution city maps may be displayed. The latter depict the *D. reticulatus* locations as yellow dots, whereby the number given refers to the data source.

Fig. 3, for example, shows a zoom of the SDM predicted habitat suitability map. Only regions with a habitat suitability index (SI) above a threshold (Youden Index, $SI > 0.5$) are classified as regions where *D. reticulatus* is present and depicted in colours ranging from orange (low, $SI = 0.5$) to red (high, $SI = 1.00$). Rasterized tick locations are displayed as an overlay (brown rectangles). The tick locations can be seen even better in Fig. 4, where they were placed over the two expert maps. These are just two examples of how the KMZ file can be used to compare *D. reticulatus* distribution maps. In the same way, the current expert map can be superimposed on the habitat suitability map, so that the combined expert habitat suitability map from Fig. 2 is obtained as an intersection. It can then be seen which regions with predicted habitat suitability were not used for the final map (Fig. 2) because they are outside the observed distribution of *D. reticulatus*. These regions mainly include Ireland, central and southern Italy, and the southern Balkans (Fig. 3). The tick locations newly recorded for this study (see supplement

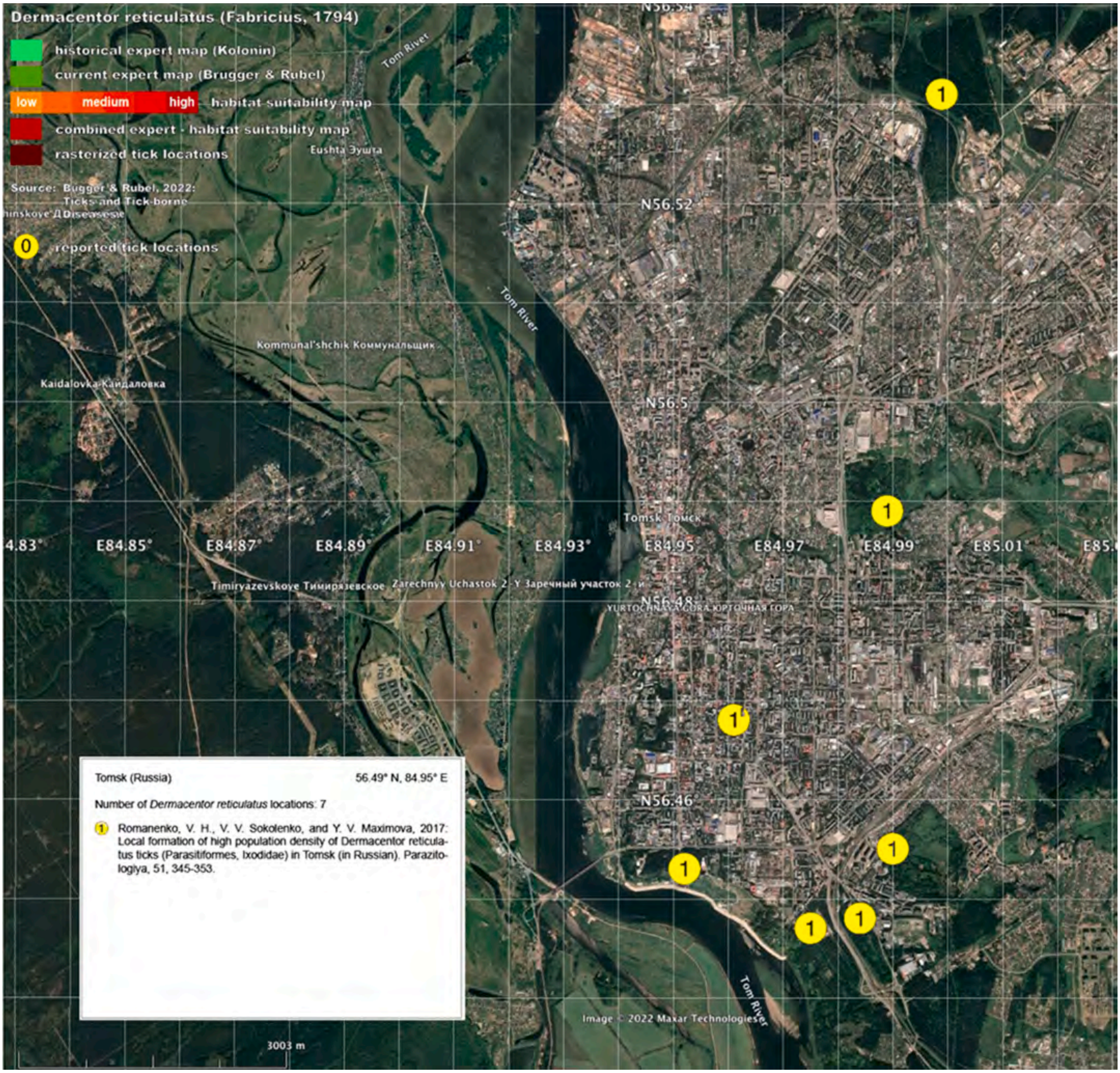

Fig. 5. *Dermacentor reticulatus* locations in the city of Tomsk (Russia).

S1) are therefore of great importance in order to differentiate between regions that have not been sampled and regions in which *D. reticulatus* has not been found, such as in Scandinavia (Kjær et al., 2019). Particularly noteworthy are the data from the publication of Dwuznik-Szarek et al. (2021), in which the closing of the gap between the western and the eastern *D. reticulatus* distribution area in Poland is described. For the neighboring north-west of Ukraine new data from Fedoniuk and Podobivsky (2020) have been included. For the first time, extensive data are now also available for the south of Ukraine (Nebogatkin, 2018). New data are also available for Russia (Vasilevich and Nikanorova, 2020) and the south-eastern part of Kazakhstan (Sayakova et al., 2019). These extensive data sets provide new insights into the distribution of *D. reticulatus*, especially in Eastern Europe. The region from Eastern Germany via Poland and the entire Ukraine, which is consistently marked with the highest habitat suitability values (Fig. 3), has not yet been shown on any global *D. reticulatus* distribution map. But individual findings are also important for the quality of the distribution maps. These include the description of three locations of *D. reticulatus* on the Black Sea coast of Turkey (Bursali et al., 2013; Orkun and Emir, 2020), where this tick species has not yet been documented on global maps despite optimal climatic conditions (Rubel et al., 2020). Two earlier references for this region, but without location information, confirm the occurrence of *D. reticulatus* on the Black Sea coast (Bursali et al., 2012). Additionally, tick locations were collected for the data sparse regions of Northern Italy (Bellato et al., 2021; Garcia-Vozmediano et al., 2021), Northwestern Spain (Gilot et al., 1976), and Southeastern England (Medlock et al., 2017).

The following eight city maps were compiled to demonstrate the urban distribution of *D. reticulatus* in public parks, fallow land, and recreational areas: Bilbao in Spain (43.26° N, 2.94° W), Grenoble in

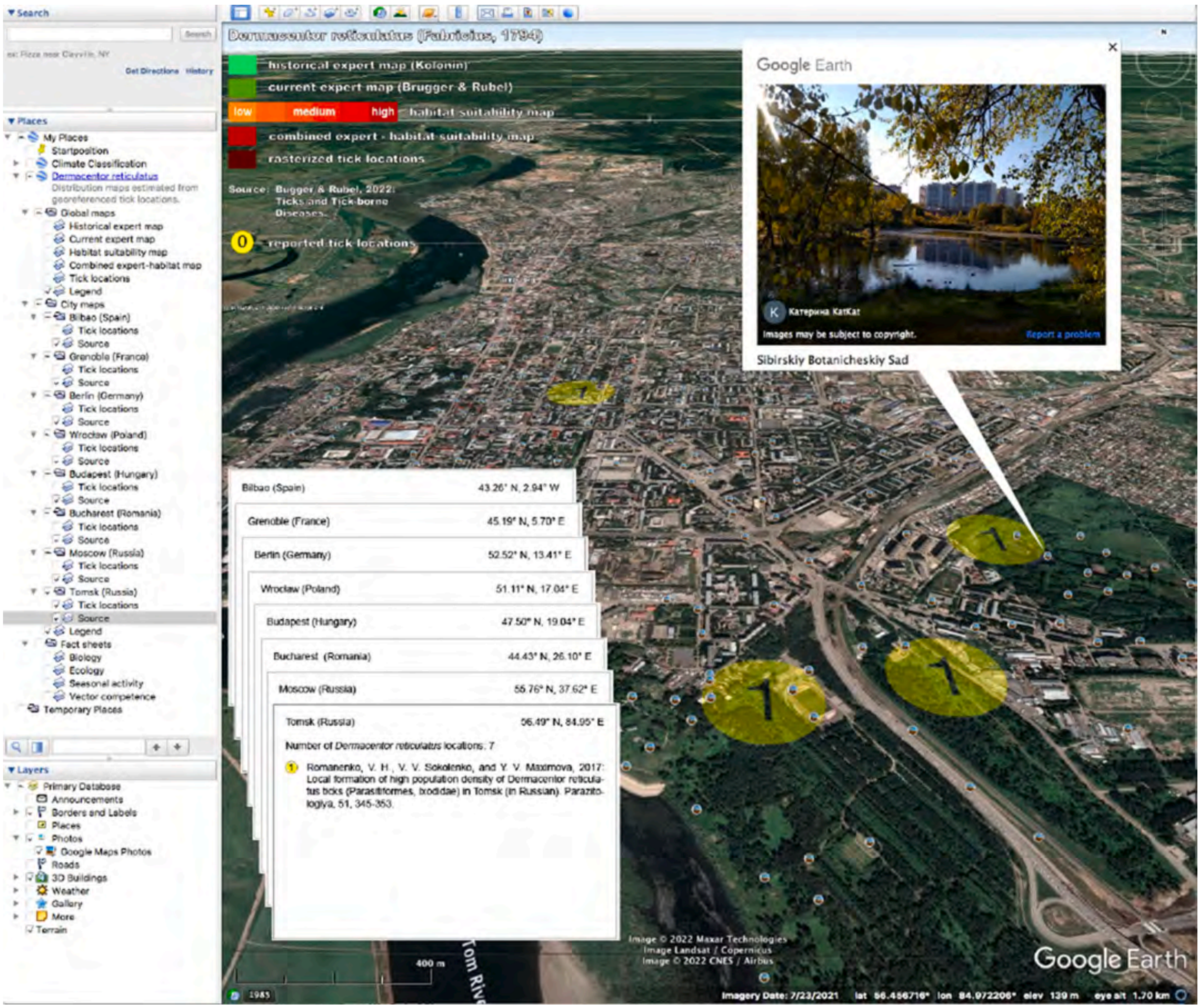

Fig. 6. Google Earth window of the *Dermacentor reticulatus* kmz file showing the available tick maps in the left sidebar. Selected is the city map of Tomsk, a zoom to the southeast of the city with transparent tick positions, a photo of the tick location in the Siberian Botanical Garden and information on the data source.

France (45.19° N, 5.70° E), Berlin in Germany (52.52° N, 13.41° E), Wrocław in Poland (51.11° N, 17.04° E), Budapest in Hungary (47.50° N, 19.04° E), Bucharest in Romania (44.43° N, 26.10° E), Moscow in Russia (55.76° N, 37.62° E), and Tomsk in Russia (56.49° N, 84.95° E). Half of these city maps are within, the other half (Berlin, Wrocław, Bucharest, Tomsk) outside of the distribution area of the historical expert map (Fig. 4). By far the largest number of studies on the occurrence of *D. reticulatus* are available for the metropolitan area of Berlin, where 237 locations of 12 tick species have been documented (Rubel et al., 2021; 2022). A representative selection of 37 *D. reticulatus* locations in Berlin, together with all other city maps mentioned above, is presented in supplement S3. As an example, two pictures of the city map of Tomsk, Russia, are shown here. Fig. 5 shows an overview of all *D. reticulatus* locations documented in Tomsk. This data set from the eastern distribution limit of *D. reticulatus* contains 7 tick locations from Romanenko et al. (2017). Fig. 6 shows another example of this city map, namely a zoom to the southeast of Tomsk. The map (yellow circles of tick locations) has been rendered transparent in Google Earth to show the underlying satellite imagery. In addition, one of the numerous photos placed in Google Earth was chosen to give an impression of the location of *D. reticulatus* in the Siberian Botanical Garden. A window with references to the data sources, which can be displayed as an overlay for all city maps, is also shown. These examples demonstrate only some of the possibilities of virtual globes available to the user to visualize the distribution of ticks.

Since the visualization of the geographical distribution of ticks on the virtual globe was also developed for non-entomologists and will later be extended to other tick species, the user can also display fact sheets on the tick species. These were deliberately kept very compact and are only intended to give a brief overview of biology, ecology, seasonal activity, and vector competence (supplement S4). Biology and ecology of *D. reticulatus* were summarized after Nosek (1972) and Hornok (2017). Studies from the entire distribution area, e.g. France (Martinod and Gilot, 1991), Poland (Zając et al., 2021), and Russia (Romanenko et al., 2017), show a similar seasonal activity. Using this information, a generalized diagram of the monthly abundance of adult *D. reticulatus* was compiled. It shows the typical spring and autumn activity peaks. Finally, a reduced table for proven vector competence, i.e. the experimental confirmed vector-to-host transmission of pathogens, was adapted from Rubel et al. (2020).

4. Conclusions and outlook

A combination of the current expert map and the distribution of *D. reticulatus* calculated with an RF model was suggested as the best distribution map. However, users are free to choose which map is best for answering their question. For example, the map calculated with the RF model shows not only the occurrence of ticks but also the habitat suitability of a region. This also includes regions in Ireland, Scandinavia, Italy, and the southern Balkans in which *D. reticulatus* has not yet been reported. Just as current findings confirm the occurrence of *D. reticulatus* on the Black Sea coast of Turkey (Bursali et al., 2013; Orkun and Emir, 2020), the first findings could also come from some of these regions in the near future. There are also indications of the occurrence of *D. reticulatus* from another region outside of the distribution area shown. This includes the molecular identification of *Babesia canis* in sheepdogs in northwestern Iran, which indicates the occurrence of *D. reticulatus* south of the Caucasus mountains (Khanmohammadi et al., 2021).

The question arises whether and how the future distribution of *D. reticulatus* will develop as a result of climate change. To answer this question, SDMs like the RF model used here are applied to future climate scenarios. However, all studies published to date have refrained from showing that the change in tick spread due to the (observed) past climate change can also be correctly simulated. The use of a SDM to predict the future distribution of a species without demonstrated model performance concerning past climate change is not acceptable and contributes to the fact that SDM predictions of future climate scenarios are increasingly critically assessed. It is therefore planned to first simulate the spread of *D. reticulatus* observed in past decades, as was recently demonstrated for *Hyalomma marginatum* (Fernández-Ruiz and Estrada-Peña, 2021). Only then can the species distribution model performance be assessed and, if possible, application to future climate scenarios considered.

Analogous to the first distribution maps of *D. reticulatus* on the virtual globe, distribution maps for *Ixodes ricinus, Ixodes hexagonus, Ixodes trianguliceps, Haemaphysalis concinna* (Rubel et al., 2018), *Dermacentor silvarium* (Rubel et al., 2020), and some other important Eurasian tick species are in progress in order to get closer to the goal of publicly accessible digital tick maps Fedoniuk and Podobivsky (2020); Nebogatkin (2018).

Declaration of Competing Interest

Authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgements

We are grateful to Igor V. Nebogatkin, I. I. Schmalhausen Institute of Zoology, Kyiv, for providing the papers in Ukrainian of cite1 and cite2, which helped fill data gaps.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ttbdis.2022.102102.

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