Global and Planetary Change 78 (2011) 54–64

Contents lists available at ScienceDirect

Global and Planetary Change

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

Projection of climatic suitability for *Aedes albopictus* Skuse (Culicidae) in Europe under climate change conditions

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ARTICLE INFO

Article history:
Received 2 August 2010
Accepted 16 May 2011
Available online 23 May 2011

Keywords:
Asian tiger mosquito
dengue
global change
global warming
species distribution model
invasion
vector-borne disease

ABSTRACT

During the last decades the disease vector *Aedes albopictus* (*Ae. albopictus*) has rapidly spread around the globe. The spread of this species raises serious public health concerns. Here, we model the present distribution and the future climatic suitability of Europe for this vector in the face of climate change. In order to achieve the most realistic current prediction and future projection, we compare the performance of four different modelling approaches, differentiated by the selection of climate variables (based on expert knowledge vs. statistical criteria) and by the geographical range of presence records (native range vs. global range).

First, models of the native and global range were built with MaxEnt and were either based on (1) statistically selected climatic input variables or (2) input variables selected with expert knowledge from the literature. Native models show high model performance (AUC: 0.91–0.94) for the native range, but do not predict the European distribution well (AUC: 0.70–0.72). Models based on the global distribution of the species, however, were able to identify all regions where *Ae. albopictus* is currently established, including Europe (AUC: 0.89–0.91).

In a second step, the modelled bioclimatic envelope of the global range was projected to future climatic conditions in Europe using two emission scenarios implemented in the regional climate model COSMO-CLM for three time periods 2011–2040, 2041–2070, and 2071–2100. For both global-driven models, the results indicate that climatically suitable areas for the establishment of *Ae. albopictus* will increase in western and central Europe already in 2011–2040 and with a temporal delay in eastern Europe. On the other hand, a decline in climatically suitable areas in southern Europe is pronounced in the Expert knowledge based model. Our projections appear unaffected by non-analogue climate, as this is not detected by Multivariate Environmental Similarity Surface analysis.

The generated risk maps can aid in identifying suitable habitats for *Ae. albopictus* and hence support monitoring and control activities to avoid disease vector establishment.

1. Introduction

The invasive disease vector *Aedes albopictus* (*Ae. albopictus*) has recently received much attention (e.g. Benedict et al., 2007; Enserink, 2008; Medley, 2010). The mosquito has been ranked among the first 100 of the Worlds´ worst invaders (Crans, 2008). It has spread from its original distribution area in South-east Asia (Hawley, 1988) to at least 38 countries in North and South America, Africa, Oceania and even Europe (Benedict et al., 2007), likely by global transport of goods (e.g. Lounibos, 2002; Tatem et al., 2006; Fischer et al., 2010a). The first European invasion of *Ae. albopictus* was reported in 1979 from Albania (Adhami and Reiter, 1998). Upon its second arrival in Europe in 1990 the mosquito managed to establish permanent populations in Italy (Sabatini et al., 1990) and is now found across the Mediterranean area (Spain, France, Slovenia, Croatia and Greece; see Suppl. Reference list).

The spread of *Ae. albopictus* raises serious public health concerns. Under experimental conditions *Ae. albopictus* is able to transmit 22 viruses (Gratz, 2004). In nature it is mainly known to be an important vector of dengue, chikungunya and West Nile. Also Yellow fever virus and eastern equine encephalitis virus (North America), Ross River virus (Australia), Usutu virus (Italy) and the heartworms *Diofilaria immitis* and *D. repens* (Italy) were isolated from specimens collected in the field (Mitchell et al., 1987; Cancrini et al., 2003a,b; Calzolari et al., 2010). Due to its rapid spread (Lounibos, 2002), broad ecological plasticity (Delatte et al., 2008b) and high population density, this species has the potential to serve as an epidemic vector. Furthermore, its capacity to vertically transmit dengue and La Crosse (Tesh and Gubler, 1975; Rosen et al., 1983) enhances the possibility of establishing diseases in new areas (Delatte et al., 2008a). In Europe, the medical relevance of *Ae. albopictus* was highlighted in 2007 when the occurrence of the species was related to a chikungunya-epidemic

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doi:10.1016/j.gloplacha.2011.05.008

in northern Italy in the region of Ravenna (Rezza et al., 2007). Recently, autochthonous cases of dengue fever were diagnosed in southern France for the first time (La Ruche et al., 2010) where *Ae. albopictus* serves as vector. Furthermore, autochthonous dengue virus infections were reported from Croatia (Schmidt-Chanasit et al., 2010; Gjenero-Margan et al., 2011).

Even under conservative and optimistic scenarios, future climate change is likely to increase air temperatures. At the end of this century the number of hot days in central Europe is projected to reach conditions that are currently experienced in southern Europe. While heavy summer precipitation is expected to increase in north-eastern parts of Europe, it is likely to decrease in the south (Beniston et al., 2007). In addition, changes in annual cold extremes are projected, whereby the largest relative warming is expected for north-eastern Europe (Goubanova and Li, 2007). These climatic changes may support a range shift and further regional establishment of *Ae. albopictus*.

As an ectothermal arthropod, *Ae. albopictus* is unable to regulate its body temperature. Hence the species directly depends on the thermal conditions of its environment. Under laboratory conditions, changes in temperature and precipitation affect the population dynamics of *Ae. albopictus*, which suggests that climate change is likely to extend the limits of its northern distribution (Alto and Juliano, 2001). Regarding a northward shift, especially temperature constraints in the cold period and decreasing photoperiod are of outmost interest, because these factors determine diapause of eggs and thus the survival of the species. The 10 °C coldest-month isotherm coincides with the separation between continuously breeding populations and those that must undergo a period of dormancy to survive cold periods in winter (Mitchell, 1988). Larval surveillance in northern Japan shows that the mean temperature of the coldest month below −2 °C is potentially lethal there (Kobayashi et al., 2002). Nawrocki and Hawley (1987) state that the −5 °C coldest-month isotherm describes the maximum northward expansion of *Ae. albopictus* in continental Asia and, presumably, also in North America. A risk of establishment in Europe is considered for areas with 0 °C or higher as cold-month isotherm (Mitchell, 1995; Knudsen, 1995). But, it is not only the limitation by low temperatures that has to be considered; warm temperatures, too, play an important role for *Ae. albopictus*. Pumpuni et al. (1992) pointed out that higher temperatures greatly reduce or prevent diapause incidences in *Ae. albopictus* specimen that were exposed to critical photoperiods. Results from natural foci in southern Brazil demonstrate that diapause apparently evolved from non-diapause or non-photoperiodic ancestors, whereby in southern parts of USA a diapause reduction was observed presumably due to rapid local adaptation (Lounibos et al., 2003). Sufficient precipitation or perhaps more generally a suitable local moisture regime is an additional prerequisite for the occurrence of the species. Moisture directly controls the availability of breeding sites and the relative humidity is an important factor for egg survival (Juliano et al., 2002). Annual precipitation is reported to be higher than 500 mm in the species' habitats in the Mediterranean area (Mitchell, 1995).

Previous approaches to map suitable climatic conditions for the establishment of *Ae. albopictus* in Europe mostly focused on the risk of invasion under current climatic conditions. Considering rainfall beside other factors (photoperiod, temperature and humidity), Mitchell (1995) developed a risk map for the Mediterranean Basin by comparing the climatic conditions of the region with the estimated climatic envelope of *Ae. albopictus*. Knudsen et al. (1996) investigated the distribution of *Ae. albopictus* in Italy and projected the risk for a broader distribution throughout Europe. This projection is based on climatic criteria identified by Nawrocki and Hawley (1987) including winter mean temperature, mean annual rainfall, and mean summer temperature. Eritja et al. (2005) used the same climatic limits as Mitchell (1995) and generated a detailed risk map for Spain, which considered regional climatic conditions. For the United Kingdom, Medlock et al. (2006) developed a GIS based model using mean monthly temperature, annual rainfall and photoperiod to assess the overwintering survival, spring hatching and production of overwintering eggs in autumn. The European Centre for Disease Prevention and Control (ECDC) produced risk maps that are aiming to predict climatic suitability of *Ae. albopictus* for the years 2010 and 2030 (ECDC, 2009). On a global scale, Benedict et al. (2007) investigated the regional risk of invasion by *Ae. albopictus*. Their analysis was carried out using eleven environmental data layers of the present climate. Recently, Medley (2010) investigated environmental (including climatic) niche shifts during the global invasion of the species, by modelling niches separately for each continent. Notably, most of the relevant literature is concerned with the present distribution and risk of invasion by *Ae. albopictus* under current climatic conditions. However, the predicted increase in temperature that is based on climate change scenarios will probably extend the spatial availability of breeding sites and also enhance mosquito survival (Woodward et al., 2001).

Our analysis starts from the assumption that *Ae. albopictus* will colonise climatically suitable niches around the world. We want to identify areas that could serve as potential habitat for the species today and in the future. Here, we assess the potential of *Ae. albopictus* to establish in Europe under projected climatic trends in the 21st century. In order to account for uncertainty in the selection of presence records and environmental variables, we (1) compare projections based on the species' former native range to those based on its recent entire global range, and (2) apply variable selection by expert knowledge as well as variable selection by an automated statistical procedure.

2. Material and methods

We created distribution models with MaxEnt, using species occurrences of the native range and of the entire range across the globe. For both training areas (global and native) two sets of bioclimatic data were prepared as input variables. One set was selected using expert knowledge on species climatic constraints. The second set was selected using solely statistical criteria. The future climatic suitability of *Ae. albopictus* in Europe was projected for two climate change scenarios. In addition, niche similarity between global and native regions and climatic similarity between projections was analysed.

2.1. Spatial distribution and presence records of Aedes albopictus

Presence records of *Ae. albopictus* at the global scale were taken from Benedict et al. (2007). Additionally, a literature search of scientific articles and reports of mosquito surveillance was conducted for the years 2003 onwards to consider additional infestations (see Supplemental Reference list). Reported occurrences of *Ae. albopictus* without evident establishment were excluded from the dataset. This resulted in a global dataset that consists of 6347 occurrence points with 4683 occurrence points just for Brazil, due to a detailed monitoring system in South America. Presence records for the United States are available on county level but not as precise geographical coordinates. Therefore the 1033 counties with documented presence records were converted to points by digitising the centroids for each of the counties.

Considering that worldwide, apart from the USA and Brazil, less than 1000 coordinate pairs were available, a random set of ten percent of the data were extracted for Brazil and the USA. Hence, the density of presence records for Brazil and the USA was reduced to levels that correspond to the density of documented presence points in other regions with maybe less intensified mosquito monitoring systems. Without this stratified subsampling, the results would have been biassed towards the climatic conditions of South and North America