European Centre for Disease Prevention and Control

TECHNICAL REPORT

Development of *Aedes albopictus* risk maps

Stockholm, May 2009

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This report was commissioned by the European Centre for Disease Prevention and Control, coordinated by Evelyn Depoortere (ECDC), and produced by

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The MODIS data used in the statistical presence/absence model were produced by David Rogers and colleagues from TALA, Zoology, Oxford (UK), as part of the EDEN project and are available to authorised users through the EDEN data management website at: http://edendatasite.com/.

Changing temperature and rainfall patterns using minimum and maximum impact climate change models/scenarios were computed by William Wint and colleagues from ERGO, a partner of Euro-AEGIS, as part of the V-borne ECDC study, and are available to authorised users through the EDEN data management website mentioned above.

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Introduction

Following the outbreaks of chikungunya virus in the Indian Ocean islands in 2005–2006 and in Italy in the summer of 2007, ECDC closely collaborated with experts in entomology to ensure a comprehensive understanding of the vector-related risk for introduction of the virus in Europe. During the entomology experts meeting in Paris in October 2007, a number of recommendations were made, one of which was related to the updating and further development of *Aedes albopictus* distribution maps in Europe.[1]

Following this meeting, ECDC contracted experts to

- produce a map that shows the precise current distribution of *Aedes albopictus* in Europe; and
- map the risk for establishment of *Aedes albopictus* in Europe, in the event of its introduction.

Methodology

Two major types of data were acquired to achieve the set objectives: 1) entomological data, including all instances of *Aedes albopictus* observation in Europe since the inception of observation; and 2) environmental data, including all relevant environmental and eco-climatic information needed to model the distribution and potential areas of spread of *Aedes albopictus*.

Climatic and weather data were obtained from different sources and included the world climatic zones, climatic baseline data at a spatial resolution of five kilometres, day- and night-time land surface temperature, and mean daily temperatures. In addition, relevant vegetation indices were obtained.

Based on the collected information, state-of-the-art GIS distribution maps were developed. In order to map the areas at risk for the establishment of *Aedes albopictus*, provided it is introduced, two different methods were used. A first model used observed presence and absence data as a basis, to which a set of predictor variables was applied (Random Forest technique, Breiman, 2001). The second model was developed based on a Multi-Criteria Decision Analysis (MCDA) approach, which takes into account expert advice in addition to the standardised variables.

Finally, based on selected IPCC[2] climate-change models and scenarios assessing maximum and minimal impact, potential changes in the short (2010) and long term (2030) were computed.

Results

Established homogenous populations of *Aedes albopictus* were identified in Albania, Croatia, France, Greece, Monaco, Montenegro, Italy, San Marino, Slovenia, Spain and Vatican City. The mosquito was observed once in 2007 in Germany, but its establishment in this region is not yet proven. It has also been introduced into Belgium (2000), but it did not become established. A special situation exists in the Netherlands, where it has been observed only inside greenhouses. For southern Switzerland, recent data suggest an onward spread, while the mosquito is present in isolated foci in Bosnia and Herzegovina, but no further details are available.

When mapping the areas at risk for the establishment of *Aedes albopictus* using the Random Forest model, the mosquito's further invasion in the Mediterranean basin both towards the east and the west is predicted. Suitability for the mosquito's establishment is confirmed for a large part of Italy, Greece and Turkey. Also, Mediterranean France and large parts of the Iberian Peninsula are suitable.

Using the second method (MCDA), all Mediterranean countries show higher suitability in the coastal areas and lower suitability in mountainous areas. Italy appears most suitable, as well as the coastal parts of Greece, Turkey and the Balkan countries. Most of southern and western France is also highly suitable. Farther north, the northern (lower) part of Belgium and the Netherlands, as well as large parts of UK and Ireland, are also suitable, although to a lesser extent.

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[1] ECDC meeting report. Consultation on vector-related risk for chikungunya virus transmission in Europe. Paris, 22 October 2007. Available from: http://ecdc.europa.eu/documents/pdf/Entomologists_071022%20.pdf

[2] IPCC: Intergovernmental panel on climate change

Taking the IPCC climate change scenarios (minimal impact scenarios) as a basis, most changes for 2010 are anticipated in two areas: in Central Europe (including the southernmost parts of Sweden), and in the Balkans. In the longer term (2030), this 'Central European zone' will reach as far as the Baltic States and cover large parts of southern Sweden. However, the 'Balkan zone' will not expand but even shrink, with parts of Romania and Bulgaria becoming unsuitable for *Aedes albopictus*. When taking into account maximum climate change impact scenarios, both the short- (2010) and the long-term (2030) changes are similar and show a significant further eastward extension, suggesting that most of Europe would become favourable for *Aedes albopictus* establishment.

ECDC discussion

The three different *Aedes albopictus* distribution maps (Annex 1, maps 1–3) provide a historical view on the progressive spread of the mosquito in Europe over the past 10–20 years. In certain areas the mosquito has become a serious nuisance, reaching high densities in the summer periods. However, the episode of autochthonous transmission of chikungunya virus in Italy during the summer of 2007 has clearly shown that the Tiger mosquito, as an important disease vector, is more than just a nuisance, and represents a true public health challenge. The updated distribution maps also show that our knowledge of the exact presence and spread of the mosquito is relatively limited: the implementation of mosquito surveillance often depends on local or regional initiatives, and these initiatives are not necessarily coordinated at a national level.

Taking into account its public health importance, it was considered important to identify the areas where the Tiger mosquito could be expected to be currently present, as well as the areas where it can be expected to establish itself and spread in case of its introduction. Two different approaches were used by the experts carrying out this project; while certain areas were identified by both methods as being at risk, some differences between the models exist, e.g. with regard to the extent of the risk for Portugal, Spain, France and Greece. Also, one method identifies zero suitability for the UK and Ireland, while the other shows that suitability cannot be excluded.

Thus it comes as no surprise that there is no certainty as to whether or not *Aedes albopictus* will establish itself in certain areas in Europe. However, the maps indicate certain areas that are at high risk and that have no mosquito surveillance measures implemented — at least not to the knowledge of the experts responsible for this project. The results presented here may assist the public health authorities in their efforts to strengthen preparedness for certain vector-borne diseases in those regions. At the same time, experience has shown that the Tiger mosquito may evolve quite rapidly by adapting to the local environment. This ability to adapt and evolve will undoubtedly contribute to increase its foothold on the European continent. Consequently, the models presented in this report will have to be updated on a regular basis.

Finally, even more disconcerting predictions were made in a third series of maps that is related to expected climate change. The IPCC suggested a range of potential future climate change scenarios; the authors of this report extracted minimum and maximum impact scenarios and used this scenarios for their short- and long-term predictions. The analysis confirmed that it is likely to experience an increase in areas which are potentially suitable for *Aedes albopictus*, both in the minimum and maximum change scenarios. While no additional strong conclusions can be drawn from these maps, they still give an indication of the areas where the Tiger mosquito may eventually appear, and where the vigilance of entomologists and public health authorities is justified.

ECDC conclusion

Given the above, it can be concluded that the temperate strains of *Aedes albopictus* are here to stay — and that they will spread. In addition, new populations may become established in other parts of Europe. Surveillance of the introduction and spread of this vector, in particular in areas at risk, is important in order to be prepared for the mosquito's role in the transmission of diseases.

ECDC recommendations

In order to prepare the maps presented in this technical report, a huge amount of work was carried out by collecting data from many entomologists all over Europe, resulting in a database containing an enormous amount of valuable information. Regular revision of this database would provide the possibility to easily update the *Aedes albopictus* distribution maps, providing relevant information for public health specialists.

The distribution maps show the areas for which no mosquito surveillance data are available, while the risk maps show which areas are suitable for the mosquito's establishment in case it is introduced. This information should support entomologists and public health experts in their efforts to ensure preparedness for mosquito-borne diseases. Additionally needed information includes the surveillance of the introduction, possible establishment and spread of other potential disease vectors, such as *Aedes aegypti*.

There are still many unknowns with regard to European *Aedes albopictus* strains for different pathogens, and further research into this topic is required. More research is also needed on the development of adapted control measures to eradicate newly established mosquito colonies and to prevent the further spread of the mosquito. Finally, in order to improve our understanding of mosquito introduction pathways and the evolution and adaptation of mosquito populations, further research is needed on the genetic homogeneity or heterogeneity of European mosquito populations.

1 Terms of reference for the development of *Aedes albopictus* risk maps (TigerMaps project)

As stated in the original request, the objectives of the TigerMaps project are two-fold:

- to produce a map that shows the precise current distribution of *Aedes albopictus* in Europe; and
- to map the risk for establishment of *Aedes albopictus* in Europe, in the event of its introduction.

More specifically, the TigerMaps contract stipulates to:

1.1 Map the current distribution of *Aedes albopictus* in Europe

'The first map, representing the current distribution of *Aedes albopictus* in Europe, should be based on vector surveillance data available on regional and/or national level in the countries. This map should make a distinction between areas with vector surveillance systems present, reporting positive or negative results, and areas without vector surveillance systems or data available. Second, where possible, the map should differentiate whether in a specific area the vector is present only in limited foci, or whether it is established rather in a widespread manner.'

1.2 Map the risk for establishment of *Aedes albopictus* in Europe, if introduced

'The four main climatic factors considered to be relevant to map the risk of establishment and abundance of *Aedes albopictus* if introduced to an area, have been agreed to be: winter temperatures, annual rainfall, summer rainfall and summer temperatures.

Thus, a map based on climatic scenarios should be developed in order to show the risk of establishment of the vector, if introduced. For the best possible result, all four factors need to be studied separately, followed by the identification of the best possible combination of all factors. Ideally, a dynamic model is needed, considering the weight of each of the determinants.

If possible and considered relevant, the number of weeks of vector activity could also be incorporated.'

2 State of the art prior to TigerMaps

A database for Europe was created that enabled Scholte & Schaffner (2007) to publish a map of the distribution of *Aedes albopictus* at administrative level three. This database relies on a pan-European network of entomologists and groups and provides information up until 2006. In their paper, the authors detail the situation for each country from a historical perspective. The paper also features a series of distribution maps for Europe for 1997, 2000, 2003 and 2007. Two GIS-based maps were generated by Medlock & Schaffner (in Scholte & Schaffner 2007) in order to analyse the impact of climatic and photoperiodic thresholds on areas of establishment and possible seasonal activity of *Aedes albopictus* in Europe; these maps were presented at the ECDC consultation meeting. In short, they depict a simple GIS approach to exploring the likely climatic limitations (winter temperature and annual rainfall) to the establishment of the mosquito in Europe (Figure i). The second map — based on an approach developed for the UK by Medlock et al. (2006) — predicts the potential seasonal activity zones of *Aedes albopictus* in Europe, incorporating weekly climate and photoperiod data, two crucial determinants of the mosquito's life cycle (Figure ii).

Figure i. Areas for possible establishment of *Aedes albopictus* in Europe based on five climate scenarios

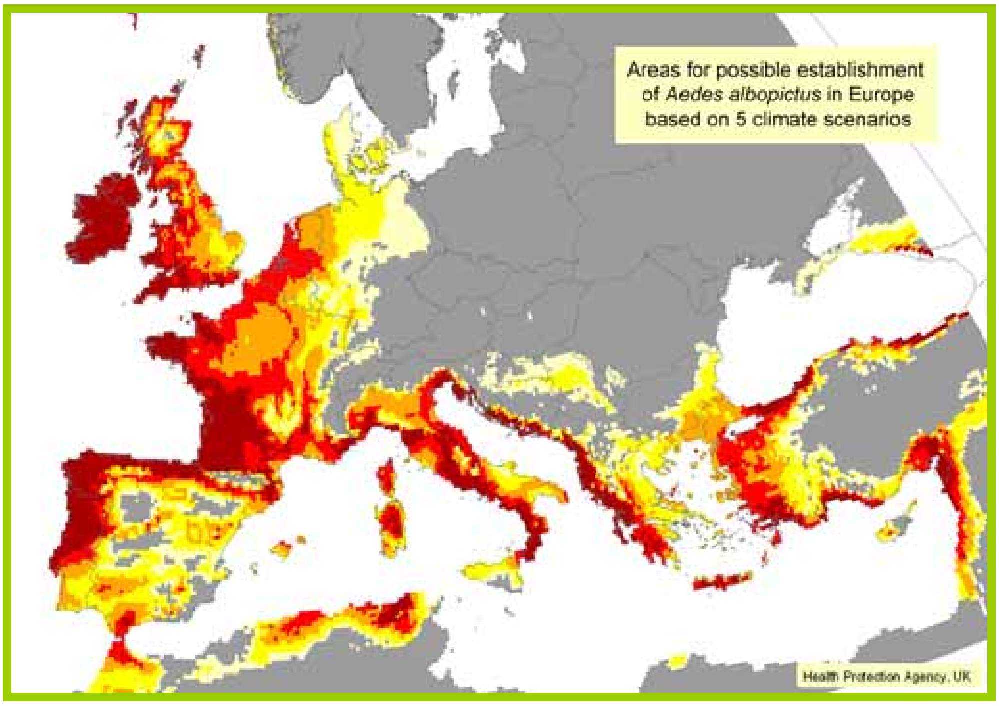
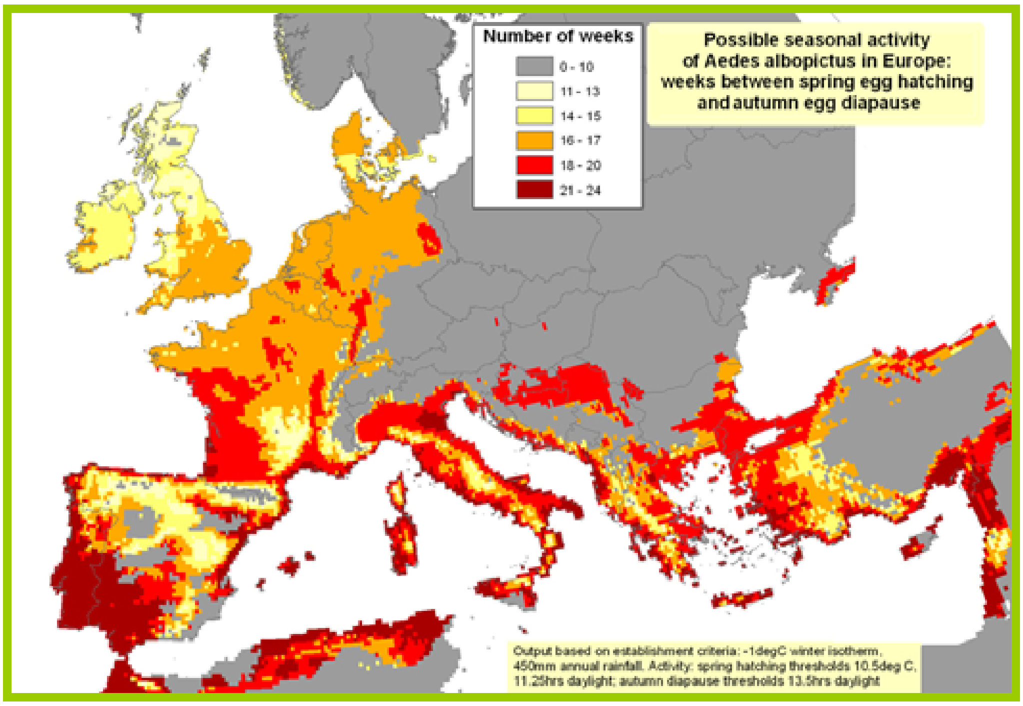


Figure ii. Possible seasonal activity of *Aedes albopictus* in Europe: weeks between spring egg hatching and autumn egg diapause

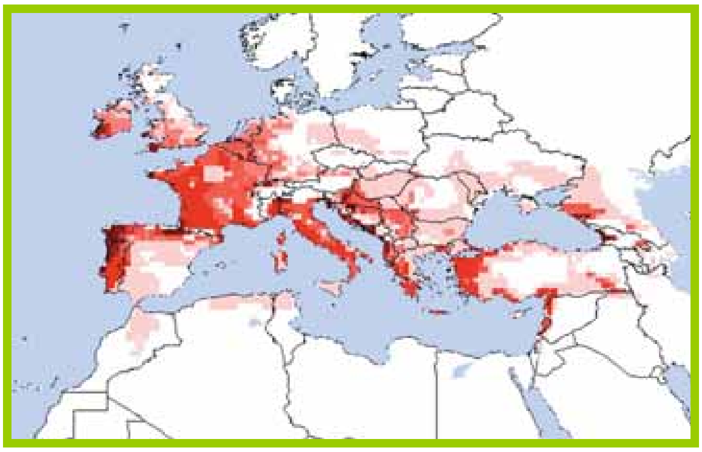


Addressing the problem on a global scale, Benedict et al. (2007) used a genetic algorithm commonly used in ecological studies — dubbed GARP, Genetic Algorithm for Rule Set Production — in order to determine the ecological niche of *Aedes albopictus* and then draft a global ecological risk map predicting the continued spread of the species. This analysis also factored in the risk of tyre imports from infested countries and the proximity to countries that have already been invaded in order to develop a list of countries most at risk for future introductions and establishments. So far, the predictions for Brazil were in line with the observed data. Figure iii shows the results for Europe.

Despite the fact that the method developed by Scholte & Schaffner (2007) for Europe is based on a simple GIS approach where areas are a priori sequentially fitted into two climatic characteristics grouped in an increasing pattern[3], there are striking similarities with the more complex model proposed by Benedict et al. (2007). However, both models do not allow for the assessment of the importance of individual predictor variables. The European model is even more limited since it was developed to assess the influence of climatic variability on creating or preventing establishment; it does not constitute a risk map.

[3] Four scenarios are included. In Figure 1 of Scholte & Schaffner (2007), areas of overlap are in a color gradient from pale yellow to dark red: (1) 450 mm annual rainfall AND -1° C mean January isotherm, (2) 500 mm AND 0° C, (3) 600 mm AND 2° C, (4) 700 mm AND 3° C.

Figure iii. Predicted potential distribution of *Aedes albopictus* in Europe. Darker colours indicate greater numbers of climate models predicting a suitable habitat, with the darkest colours signifying 10 concurring models (adapted from Figure 2 in Benedict et al. 2007)



Given the above, it was concluded that it is important to develop a modelling approach that includes expert advice on selecting a sub-set of environmental predictor variables that allow more accurate predictions on areas suitable for the establishment and the spread of *Aedes albopictus*, should it be introduced.

3 Methodology

Task 1. Data collection and processing

Two major types of data were acquired to achieve the objectives of TigerMaps: 1) an entomological dataset including all instances of *Aedes albopictus* observation in Europe since the inception of observation; and 2) an environmental database including all relevant environmental and eco-climatic datasets needed to model the distribution and potential spread areas of *Aedes albopictus*.

Task 1.1. Entomological dataset

Three types of entomological data were collected: 1) geo-referenced data on presence/absence and, when available, abundance, of *Aedes albopictus*; 2) information on past and present survey/control activities on mosquitoes in general and *Aedes albopictus* in particular; and 3) information on *Aedes albopictus* activity/dynamics under local climatic conditions.

Database set-up

The TigerMaps data were organised in an Excel database which may serve as a basis for further annual updates by ECDC: <TigerMaps-EntomoDataSet-080731.xls>. The geographic location of the data is predominantly related to administrative boundaries. The definition/ nomenclature of the different administrative levels is rather complex in Europe and varies from country to country. The data are presented at two levels of aggregation in the database: one worksheet with larger administrative units (comparable to counties) which includes 52 states, and a series of 16 separate worksheets with smaller units (typically municipalities) covering the 16 EU countries with recent records of *Aedes albopictus* presence. Therefore the pan-European worksheet provides information which is cruder (less geographic detail) than the 16 country worksheets (more geographic detail).

In technical terms, the first worksheet <Euro_NUTS3-LAU1> includes information at a 'high' administrative level. At this level, data are arranged for administrative level NUTS[4] 3 (sometimes LAU[5] 1, LAU 2 for Andorra) if found more suitable for mapping, depending on the country. In this worksheet, four administrative levels are reported (see Table 1): Admin1 (country), Admin2 (NUTS 1; mostly states/regions), Admin3 (NUTS 2; mostly states/regions/provinces), Admin4 (NUTS 3). These data are provided for all countries in Europe: geographical, political, and continental (see Table 6).

Table 1. Entomological dataset: fields for 'high' administrative levels, Europe (worksheet <Euro_NUTS3-LAU>)

Data related to locality // GIS							
Admin1: Country		Admin2: NUTS 1/2		Admin3: NUTS 2/3		Admin4: NUTS 3/LAU 1	
Code	name	Code	name	Code	name	Code	name

The 16 country worksheets <XX_LAU2> (XX= country code) concern the 'low' administrative level, which provides data at administrative level LAU 2 (municipalities). Higher administrative levels are indicated, and more precise locations such as village locations or geo-references for point data (see Table 2) are given if available. These worksheets are only provided for the 16 countries/states in which *Aedes albopictus* was observed at least once prior to January 2008 (Table 6).

[4] NUTS = Nomenclature of Territorial Units for Statistics, three levels

[5] LAU = Low Administrative Unit, two levels

Table 2. Entomological dataset: fields for 'low' administrative levels, per country (e.g. Albania: worksheet <AL_LAU2>)

Data related to locality // GIS												
Admin1 code_ country	Admin1 name_ country	Admin2 code	Admin2 name	Admin3 code_ county	Admin3 name_ county	Admin4 name_ district	Admin4 code_ municipality	Admin5 code_ country	Admin5 name_ municipality	Admin6 name_ village	Geo-references 1 Latitude	Geo-references 2 Longitude

Data on presence/absence and abundance of Aedes albopictus

The aim of the project was to establish presence and absence of *Aedes albopictus* in space and time. Criteria include: continuously present in time (established population), sporadic (mosquito needs reintroduction), present as a single focus or more widespread in a given area, consistently absent, etc. All data records were linked to geographic coordinates. Ideally, these are GPS point measurements of longitude and latitude, but considering that in most cases it was only possible to relate records to the closest geographic feature, we tried to establish a relationship with the municipality as the smallest possible administrative unit (polygon).

To achieve this, the database established by Scholte & Schaffner (2007) was used as a basis. All experts that originally contributed to this database were contacted again to check the validity of existing records, to add new data where available (e.g. confirm established populations, sporadic introduction hotspots, new introductions, etc.), to enquire about existing gaps, and improve geo-referencing. In this context, the input of more than 50 professionals in Italy deserves credit. Data were provided through the courtesy of Dr R Romi (ISS, Rome), Dr P Angelini (Regione Emilia Romagna), Dr R Bellini (CAA, Crevalcore), Dr C Venturelli (AUSL Cesena), Dr A Talbalaghi (Mosquito Control Piedmont/Piemonte), and Dr R Zamburlini (University of Udine), and many others. Italy, as the most affected front-line state, was particularly important in this respect. Another important aspect of the project was the establishment of new contacts in countries that had not been active in the former network, especially northern and eastern countries.

In the database, the presence or absence of *Aedes albopictus* ('yes' or 'no') as well as the unavailability of information is indicated. Unavailable data are referred to as either 'no data' (local scientists have no information on a given area, or do not know of any scientist surveying mosquitoes in that area) or as 'no information' (no information on a given area available). In addition, information was collected on presence (if present in 2007, since when (year); if not present in 2007, estimated former period of presence (year/s)); on the type of occurrence ('homogenous' or 'isolated foci'); on the report of nuisances ('complaints' or 'no complaints'); and on the source of information ('publication', 'newspaper' or 'personal communication'). Corresponding data fields with modalities are depicted in Table 3.

Table 3. Entomological dataset: fields related to the occurrences of *Aedes albopictus*

Data related to Aedes albopictus					
Presence 2007	If yes, since	If no, estimated period of presence (before 2007)	Type of occurrence	Report of the nuisance	Source of information
Yes/no/ no data	year	year/s	Homogenous/ isolated foci	complaints/ no complaints	Publication/newspaper/personal communication

Data on mosquito surveillance and control

An important aspect of this study was to identify areas where active surveys were conducted. This helped to assess the quality of available data and highlight areas where information is weak or missing. In combination with the modelling approach (see Task 2 below) this aspect might become instrumental in establishing priorities for future surveys.

To achieve this, current mosquito surveillance, i.e. surveillance with no particular focus on *Aedes albopictus*, and related control activities were mapped. As a starting point, the above-mentioned contributors were asked to list the existence or absence of known regional and national surveillance/research studies (yes/no). Just as for the entomological data mentioned earlier, data absence is referred to as 'no data' or 'no information'. Additional information on the timing of these activities is also given. Since this information is used as part of the data quality control check, only information related to the last five years (2003–2007) was included.

In addition, specific activities related to *Aedes albopictus* and other exotic mosquitoes were also recorded: surveillance ('yes', 'no', 'no data' or 'no information'), the type of surveillance ('active', i.e. active research on mosquitoes, or 'passive', i.e. report of nuisance biting on humans), implementation of surveillance (year), control activities ('yes' or 'no'), type of control programme ('larval', 'adults' or 'both'), and organisation ('public', 'private' or 'both') of control programmes against *Aedes albopictus*. Corresponding data fields with modalities are shown in Table 4.

Table 4. Entomological dataset: fields related to surveillance and control, for *Aedes albopictus* and for other mosquitoes in general

Data related to other mosquitoes				Data related to Aedes albopictus					
Surveillance/ study	Regular surveillance active since	Control	…	Surveillance	Type of surveillance	Surveillance active since	Control	Type of control programme	Organisation of control programme
yes (date)/no/ no data	year	yes/no/ no data		yes/no/ no data	active/ passive	year	yes/no	*larval/ adults/ both*	public/ private/ both

In summary, three types of fields constitute the entomological database: fields related to locality (e.g. administrative levels or geo-referenced point data, colour-coded blue, with data in grey); fields related to *Aedes albopictus* in orange; and fields related to other mosquitoes in green.

Data on Aedes albopictus activity/dynamic

In order to validate and/or improve the climate parameters used for modelling the potential distribution and activities of *Aedes albopictus*, especially for the seasonal activity map, a supplementary dataset was created, listing all available and defined geo-referenced point data, and the dates of first and last oviposition.

Task 1.2. Environmental dataset

Climatic and weather data were obtained from different sources: meteorological stations, ground-measured interpolated grids and remotely sensed derived temperature data.

World climatic zones

World climatic zones derived by Köppen (1936) and updated by Peel et al. (2007) were used to delineate similar climatic zones for the presence of *Aedes albopictus*.

Temperature and rainfall

Climatic baseline data were obtained from the Climate Research Unit (http://www.cru.org) at a spatial resolution of five kilometres. These data represent monthly mean temperatures and rainfall variables averaged from 1961 to 1990 and are considered reference data by the International Panel on Climate Change (IPCC) for all climate scenario models. Wint et al. (2008) used these data for various climate change scenarios that were acknowledged by IPCC within the framework of the V-borne project (ECDC). For MCDA (Multi Criteria Decision Analysis) modelling, the scenarios representing, respectively, the minimal and maximum change scenarios are retained. For both scenarios the corresponding temperature and rainfall data for 2010 and 2030 are used to asses the influence of the short-term and long-term climate change.

Day- and night-time land surface temperature was obtained from the EDEN Data Management Team archive (http://edendatasite.com/) at a spatial resolution of 1 km. Scharlemann et al. (2008) pre-processed the data using the following procedure: MODIS 8-day composite images were enhanced using a spatial and temporal spline transformation prior to a Fourier transformation. The first three harmonics of the Fourier transform were retained for analysis. In addition to Fourier-processed data layers, minimum, maximum and diurnal change variables were derived. The MODIS images were projected from the original sinusoidal projection into geographic projection (WGS84) and constructed as a mosaic.

Mean daily temperatures between 1995 and 2007 were obtained from the Temperature Data Archive at the University of Daytona (http://www.engr.udayton.edu/weather/). The daily records were transformed into the number of days with temperatures higher than 11° C (Kobayashi et al, 2002). First, the total number of days with temperatures exceeding the threshold was calculated, and then the degree days were calculated by summing up the temperature and subtracting the threshold of those days. The database was then spatially joined to a geo-referenced city data layer (http://www.esri.com).

Vegetation indices

Two vegetation indices, the Normalised Differencing Vegetation Index and the Enhanced Vegetation Index were obtained from the EDEN Data Management website at a spatial resolution of 1 km (http://edendatasite.com/).

Task 2. Mapping and modelling

Task 2.1. Mapping the observed presence of *Aedes albopictus*

Based on the existing information, state-of-the-art GIS maps are provided, depicting:

- presence and absence of *Aedes albopictus* at the smalles available spatial resolution;
- the actual year of presence is mentioned when occasional presence over time was recorded;
- two different spatial distribution patterns are highlighted (focal or continuous) when continuous presence over time was confirmed; and
- different levels of monitoring and control are highlighted: classification depends on acquired information.

Task 2.2. Modelling the potential distribution and activity of *Aedes albopictus*

Random Forest model based on observed presence/absence

For all municipalities with recorded presence/absence the centroid of each municipality was calculated and a training sample (n_{train}=300), divided over both the presence (n_p=165) and absence (n_a=135) category, was selected.

The 57 data layers (*i.e.* first three amplitudes and phases of the Fourier transforms, mean, minimum, maximum, variance, variance of annual, bi-annual and tri-annual cycle, combined variance of annual, bi-annual and tri-annual for daytime land surface temperature (LST), night-time LST, NDVI and EVI) and annual rainfall were standardised prior to the statistical modelling to facilitate model output interpretation. Per training site, the corresponding values were extracted from each raster data layer.

As a next step the set of predictor variables was entered into a Random Forest, which is a newly developed ensemble learning technique (Breiman, 2001). The Random Forest technique was selected over other more classic, statistical based models such as logistic regression because it does not have to obey any statistical constraints and because they can robustly cope with correlation between the predictor variables. Moreover it outperforms statistical modelling techniques in classification problems (Prassad *et al.*, 2006; Peters *et al.*, 2007). In addition the relative importance of predictor variables can be estimated, thus making Random Forests biologically interpretable.

Random Forests generate *k* classification trees that are aggregated to produce the final classification. For modelling the presence of *Aedes albopictus*, the number of trees *k* was set to 200. Based on the variable importance a step-wise backward reduction of the number of variables was performed to avoid an overly complex model. Although including all the variables will not affect the model performance, it will hamper its interpretation. At each step the variable with the least importance was dropped from the model until the accuracy dropped below 90%.

In Random Forests, the accuracy of each model is automatically measured using the so-called out-of-bag error. The out-of-bag error of a Random Forest is calculated as follows:

1. Assume a model with *k* trees (*k*=200)
2. For each tree
   a. Construct the tree using a different bootstrap sample (total number of bootstrap samples = *k*) from

the original data sample; the sampling is generated with replacement. This bootstrap sample consists of approx. 2/3 of the dataset (size = *n*)

   b. The other *n*/3 are the so-called out-of-bag elements not used to generate the tree
   c. These out-of-bag elements are classified once the tree is generated and serve as test set

3. Calculate the out-of-bag error as the proportion of misclassification (%) over all out-of-bag elements (*k* * *n*/3 elements)

Once the out-of-bag error is determined, the Area Under Curve (AUC) from the Receiver Operator Characteristic is used to assess the model quality.

Multi Criteria Decision Analysis (MCDA) based on expert advice

The Multi Criteria Decision Analysis approach was developed in the V-borne project (ECDC) and further refined in this project. The temperature and rainfall variables were standardised into an interval between [0,255] prior to modelling. Following expert advice (Medlock, Schaffner, and Scholte; personal communication) sigmoidal membership functions were determined. For each parameter, the parameters in Table 5 were used. For a sigmoidal function, the lower threshold indicates that below this limit suitability is zero while values above the upper limit indicate maximum suitability. For a symmetrical sigmoidal function, the maximum suitability is reached between the second and third threshold value, while below and above the lowest and highest threshold value suitability will be zero. This way, each individual membership function will transform the original data layer on a per-pixel basis into a suitability map scaled between [0,255] for *Aedes albopictus*.

Table 5. Expert parameters for the presence of *Aedes albopictus*

Variable	Threshold	Function
Annual precipitation	450 – 800 mm	Sigmoidal
Temperature January	-1° C – 3° C	Sigmoidal
Summer temperatures	15°-20°-30°-35° C	Symmetrical sigmoidal

In a further step, the individual suitability data layers were combined using a linear combination method. Each factor was assigned equal weight and added, using the following equation:

$$y = \sum a_i x_i$$

a_i = weight

x_i = factor.

The summed output is then again scaled to the interval [0,100] and represents the combined suitability map for *Aedes albopictus*.

Potential activity period of Aedes albopictus in Europe

A GIS model, originally developed by Medlock et al. (2006) to simulate the factors crucial to the life cycle of temperate strains of *Aedes albopictus*, was applied to Europe. The model was developed using ESRI ArcGIS, Spatial Analyst and ArcObjects (ESRI, Redlands, CA) and incorporated datasets for photoperiod (generated using astronomical equations of sunrise and sunset) and climate average data for mean monthly temperature for Europe on a 10-minute resolution (New 2002). The mean monthly climate data for temperature was converted to mean weekly temperature using a continuous piecewise quadratic function, preserving the mean maximum temperature over each monthly period.

The GIS model, as detailed in Medlock et al. (2006), calculates firstly the predicted number of weeks elapsing between the first hatching of overwintered eggs in spring and the production of diapausing eggs in response to a critical photoperiod in late summer. Secondly, it calculates the predicted number of weeks elapsing between first egg hatching and possible adult die-off in early winter.

Input parameters:

Autumn diapause

The actual timing of the onset of diapause in newly produced eggs appears to be correlated with specific critical photoperiod thresholds. Given the mosquito's ability to evolve and adapt to its surroundings, the actual threshold photoperiod appears to vary geographically. A critical daylight threshold of 13 to 14 hours was reported in strains of *Aedes albopictus* from Shanghai and Nagasaki (Wang 1966, Mori et al. 1981), North America (Pumpuni et al. 1992), and Italy (Toma et al. 2003). In another Nagasaki study, a critical photoperiod of 11 to 12 hours was reported (Kobayashi et al. 2002). In Italy, some eggs were able to hatch with a day length of 10 hours (Toma et al. 2003). For the purpose of this model, the more common critical photoperiod of 13.5 hours of daylight was incorporated.

Overwintering criteria

It is generally accepted that a winter isotherm of between -3° and 0° C is a limiting factor for establishment (Nawrocki & Hawley 1987; Mitchell 1995; Kobayashi et al. 2002), however these winter isotherms were not used as limiting factors within this output, as they are considered in the statistical model.

Spring egg hatching

Studies by Toma et al. (2003) reported adult *Aedes albopictus* in Rome to be active from late March. Based on a three-week development time (at 14 to 18° C) from egg hatch to pupation (Galliard & Golvan 1957; Udaka 1959; Chan 1971; Hawley 1988), it was assumed that the first overwintering eggs hatched when daylight reached 11 to 11.5 hours and the mean temperature reached 10 to 11° C (Toma et al. 2003). These parameters were used to simulate egg hatching in spring.

A comparison between Europe, the USA and Japan

The current distribution of *Aedes albopictus* is within the humid temperate climate zones, Cfa and Cfb, in the northern hemisphere. In this zone, presence data from the USA and findings by Kobayashi et al. (2002) in Japan were contrasted with the European setting, based on the annual mean temperature and the daily mean temperature records. These countries were selected because it has been shown that for both the USA and for Europe the main introduction of *Aedes albopictus* was through the import of scrap tyres from Japan (Benedict et al. 2007, Scholte & Schaffner 2007).

Based on daily meteorological observations, the number of days with mean temperatures exceeding 11° C was calculated. Also calculated was the temperature sum when the threshold was exceeded (degree days). The accumulated temperature was calculated by subtracting 11° C from the daily mean temperature and summing these data. For the US, the average (minimum and maximum of both number of days over 11° C) and degree days per county were derived. This is the same procedure that Kobayashi et al. (2002) used, so results can be compared.

The annual mean temperature was converted into isotherms, and the number of points falling within each isotherm zone was determined.

Task 2.3. Modelling the impact of climate change scenarios

Based on selected IPCC climate-change models and scenarios assessing maximum and minimal impact, a set of predictive temperature and rainfall data layers was computed by Wint et al. (V-borne project report, ECDC, July 2008) that reflect potential changes in the short (2010) and long term (2030).

Since expert variables used in the MCDA model are all derived from temperature and rainfall, the analysis can be repeated using the prospective variables.

4 Results

Output: The maps and data layers used to produce them will be made available to ECDC in electronic GIS format compatible with the GIS software used at ECDC. Formats and legends will be discussed with ECDC staff by e-mail. The project budget does not include the printing of maps.

The different map outputs are shown in the annex to this document and are referred to as follows in the discussion below:

Figure 1. Current distribution of *Aedes albopictus* in Europe.

Figure 2. Current distribution of *Aedes albopictus* in the Mediterranean basin.

Figure 3. Current and historical distribution of *Aedes albopictus* in Central Europe.

Figure 4. Distribution risk map for *Aedes albopictus*, statistical model.

Figure 5. Distribution risk map for *Aedes albopictus*, MCDA model.

Figure 6. Potential weeks of activity of *Aedes albopictus* in Europe — spring hatching to adult die-off.

Figure 7. Prospective impact of climate change on *Aedes albopictus* distribution in Europe.

Figure 7a. Minimal impact: short-term change scenario.

Figure 7b. Minimal impact: long-term change scenario.

Figure 7c. Maximum impact: short-term change scenario.

Figure 7d. Maximum impact: long-term change scenario.

In addition, a table with entomological data was produced:

Table 6 (see Annex). Entomological data on surveillance and control of *Aedes albopictus* and other mosquitoes, and source of information, for European states.

4.1 Distribution map

General comments

Only confirmed data on the presence or absence of *Aedes albopictus* were used. Confirmed positive municipalities or locations are based almost entirely on surveillance data using ovitraps (traps that monitor egg laying). In a few cases, experts could confirm presence based on adult specimen and despite the lack of a surveillance system (neither active nor passive); these cases were included in the dataset. In contrast, when experts strongly suspected the presence of this mosquito species in a certain area but had no actual data, these suspected *Aedes albopictus*-positive areas were not included in the dataset (and maps), but were mentioned and discussed in the comments below.

Data were collected from 52 'states' (countries, microstates or territories having an ISO/NUTS national code). These are either members of the European Union or located in, or close to, geographical Europe (e.g. Cyprus, Madeira, Azores).

Major findings (see Figures 1, 2, 3 and Table 6):

The presence or absence of *Aedes albopictus* could not be assessed for 24 states. For 6 states (Belarus, Iceland, Malta, Moldova, Macedonia, and Ukraine) no feedback was received from contacted scientists. For 18 others (Austria, Bulgaria, Estonia, Finland, Faroe Islands, Gibraltar, Hungary, Ireland, Kosovo, Liechtenstein, Lithuania, Luxembourg, Latvia, Norway, Poland, Portugal, Romania, and Russia) no or very little updated information is available on the local mosquito fauna (studies are implemented only in localised areas and/or conducted on an occasional basis) and no specific surveillance for *Aedes albopictus* was implemented.

For the remaining 28 states, general information on mosquito fauna is sufficient to assess presence or absence of *Aedes albopictus*, mainly on the basis of regular mosquito surveillances or studies in large parts of the territories. Over the last five years, 12 countries have implemented specific surveillance for *Aedes albopictus* and other exotic mosquitoes. Some countries maintain surveillance at national and regular levels, both actively (i.e. Belgium, France, Netherlands) or passively (i.e. United Kingdom, Serbia).

As a result, *Aedes albopictus* was observed at least once in 16 states, but the quality of information and data varies, from national and regular surveillance to a total absence of surveillance. Major findings are:

- *Aedes albopictus* was eradicated, albeit temporarily, from some of the introduction foci in Croatia, France, Italy and Switzerland, thanks to preventive surveillance and rapid application of control measures, and it has not become established in Belgium after introduction;
- it was observed once in 2007 in Germany as well as in Switzerland (north of the Alps), but its establishment in these regions is not yet proven;
- it is regularly (re)introduced to the Netherlands, but it has not yet been observed spreading outside greenhouses, therefore it cannot be considered as established in this country;
- it is regularly introduced into southern Switzerland, and sustained control measures prevented its establishment and spread until 2006, but recent data suggest an onward spread;
- it is present in isolated foci in Bosnia and Herzegovina, but information is too scarce to confirm this with more accuracy; and
- it has established homogenous populations and could be considered as spreading in 11 countries and micro-states: Albania, Croatia, France, Greece, Monaco, Montenegro, Italy, San Marino, Slovenia, Spain and Vatican City.

Comments per country

The comments below focus on the most important historical introduction events and include the latest available information. More information on historical facts can be found in Scholte & Schaffner (2007).

Albania

- Introduction
  - Publications: Adhami & Murati (1987); Adhami & Reiter (1998).
  - First report of nuisance: 1975, complaints.
  - Discovery: August 1979, Laç; observation after complaint.
  - Pathway: imports from China, in cargo (not by tyres).
- Current situation
  - First recommendation of preventive measures in 1979 leads to a reduction of mosquito population size.
  - Surveillance: no surveillance, study, or control programmes implemented for mosquitoes in general; however, *Aedes albopictus* was occasionally surveyed, leading to the availability of three sets of data for 1979, 2001 and 2006.
  - Control: in some tourist areas, hotel owners apply adulticides when mosquito density is high.
  - Distribution: available data show a scattered distribution of *Aedes albopictus*, based on scattered surveillance, as only a few locations were investigated (27 of 374 municipalities, 7.2 %); however the species is most probably present as a homogenous population in all coastal areas, from the coastal areas all the way up to 690/700 m above sea level.

Italy

Note regarding data collection: Information about *Aedes albopictus* in Italy is vast[6]. However, precise data on *Aedes albopictus* distribution at the municipality level is scattered. This is mostly due to the fact that mosquito surveillance activities are carried out only in a limited number of areas, and, more importantly, they are not coordinated nationally. Instead, when mosquito surveys are organised, they are coordinated mostly at the municipal or regional level, carried out either by the National Institute of Health (ISS, Rome), local public health units (USLs), municipalities, universities, or private PCO companies. Since information on the presence or absence of the Asian tiger mosquito in Italy is so scattered, information was collected from 1) official publications (in scientific journals, on municipality websites, or in local newspapers if they mentioned confirmed identification of the mosquito species); 2) existing *Aedes albopictus* surveillance datasets; 3) contacts with colleagues involved in surveillance activities at the National Institute of Health (ISS, Rome), local public health units (AUSLs), universities, municipalities, private PCO companies; and 4) from a handful of *Aedes albopictus* experts with first-hand confirmation of *Aedes albopictus* presence from the field but without official surveillance. A large number of scientists and experts contributed to this project. Almost all data are based on results from active (ovitrap-based) and passive surveillance and confirmed diagnoses. Although the authors tried to be as thorough and conscientious as possible while acquiring data, it is recognised that they did not have access to all available information, and efforts continue to complete this database.

[6] Looking at the number of sites that discuss a subject is roughly indicative of its relative importance, although one should be aware of the limitations of online information and acknowledge that this is by no means a scientific approach: Google returns 125 000 hits on 'zanzara tigre', the Italian translation of Asian tiger mosquito. To put this into perspective, Google lists only 160 000 hits for '*Aedes albopictus*', and a mere 83 000 for 'Asian tiger mosquito'. This shows that approximately 80% of all internet occurrences of the Asian tiger mosquito are in Italian.

- Introduction
  - First publication: Sabatini et al. (1990).
  - First report of nuisance: Genoa, 1990.
  - Discovery: September 1990, Genoa.
  - Pathway: used-tyre import from USA, several times.

- Current situation

  Aedes albopictus is present in large parts of Italy, and Italy is by far the most heavily infested country in Europe. The only Region in Italy that appears to be entirely free of *Aedes albopictus* is the Aosta Region in the north-western area of Italy, in the Alps. All other Regions have infested municipalities, although some Regions are more heavily infested than others. *Aedes albopictus* was recorded in 1 213 (15 %) of the 8 102 municipalities. The most infested areas are those in the north-east (Veneto Region and Friuli-Venezia-Giulia Region), the area between the Alps and the Apennines (large parts of Lombardia and Emilia Romagna Regions), and the coastal areas of central Italy. In these areas, not only are many of the municipalities infested, but estimated mosquito population densities are also often higher compared to other areas. Generically speaking, *Aedes albopictus* is present in many coastal municipalities in northern and central Italy. The delta areas (Po River delta and the delta areas of the Veneto Region and the Friuli-Venezia-Giulia Region) and areas up to 500 metres in altitude in northern Italy are most heavily infested. This is shown by the proportion of infested municipalities in the three most heavily infested regions. In the Emilia Romagna Region (Po River delta), 263 of 341 municipalities are infested (77 %). In the Friuli-Venezia-Giulia Region, 139 out of 219 (63.4 %) are infested. Almost all of these locations are in low-lying areas, located between the foothills of the Alps ('Pre-Alps') and the Adriatic Sea. In the Veneto Region, 50 % of the municipalities are infested (291/581), predominantly in the area south of the Pre-Alps and the Alps.

  Almost all areas in mountainous areas above 500 meters above sea-level are free of *Aedes albopictus*. However, several experts mentioned that in the Pre-Alps and the Apennines, *Aedes albopictus* can sometimes be found in small populations in villages at altitudes of 500 m and above, located in areas with roads that lead from heavily infested areas in lower elevations to regions in higher altitudes. It is hypothesised that *Aedes albopictus* is transported by humans through road-traffic from heavily infested areas, and that small populations may become established in those villages, but that they are not likely to reach high population densities.

  Relatively few reports on the presence of *Aedes albopictus* originate from the southern areas of Italy, although several experts claim that it is very likely that many coastal areas in regions of Sicily, Calabria, Puglia, Basilicata, Campania, Molise, Abbruzzo, and Sardinia are infested. This assumed under-reporting is probably due to reduced surveillance activities in these areas.

  When acquiring observational entomological data, the authors also asked for information on control practices of *Aedes albopictus* and mosquito control in general. It could be argued that control actions might result in eradication of the species in a certain area, and therefore affect the distribution of the species. However, eradication of the species due to control actions in Europe was successful in a limited number of cases (mostly in France, but also in a few cases in Italy) but only in cases where population density was low. Generally speaking, since control of *Aedes albopictus* in Italy occurs almost exclusively at locations where the species is abundant and causes biting nuisance, control actions generally reduce population sizes rather than eradicate the species from that location. As a result, it is hypothesised that control actions generally do not affect the distribution of *Aedes albopictus* in Italy.

France

- Introduction
  - First publication: Schaffner & Karch (2000).
  - First report of nuisance: 1998 (used-tyre storage, Vienne).
  - Discovery: autumn 1999, used-tyre storages, Orne and Vienne.
  - Pathway: evidence for used tyres import, road traffic to Côte d'Azur, and ferry traffic from Italy to Corsica.

- Current situation
  - Surveillance: regular regional surveillance and control programmes have been implemented in several regions, under local administrations. An active surveillance programme for *Aedes albopictus* and other exotic mosquitoes was established in 1999; it is organised at the national level and funded by the state health authority. Surveillance was strengthened in 2006, when a chikungunya virus outbreak occurred in French overseas departments.
  - Control: control measures are in place since 2000 in all new localised foci; measures are taken by

local agencies upon request of national health authorities; in case of homogenous established populations, national health authorities fund control measures in 'risk' areas (around imported cases of dengue and chikungunya), while local (department) authorities fund routine mosquito control.
  - Distribution: the species was eliminated from six foci (five were tyres storages, one a motorway parking area) along with other exotic species, but since 2005 *Aedes albopictus* has been spreading in two areas in Corsica (where a first introduction without establishment was observed in 2002) and on the French Riviera (where control measures have slowed down its spread after its first introduction in 2003).

Belgium

- Introduction
  - First publication: Schaffner et al. (2004).
  - First report of nuisance: no report to date.
  - Discovery: October 2000, Vrasene, Oost-Vlaanderen, used-tyre storage.
  - Pathway: evidence for used tyre import.
- Current situation
  - Surveillance: a country-wide four-year research programme (MODIRISK) on mosquito biodiversity started in 2007, aimed at evaluating mosquito fauna and associated vectorial risk; this programme includes active specific surveillance of *Aedes albopictus* and other exotic mosquitoes.
  - Control: to this date, no control programmes implemented.
  - Distribution: only a few specimens of *Aedes albopictus* were observed in one focus in 2000. In 2003 and 2007, no specimens were found. Since no control programmes were in effect, it is assumed that the species was unable to become established due to unfavourable climatic conditions and/or a founder population that was too small. Therefore, a viable wild population could not become established.

Montenegro

- Introduction
  - First publication: Petrić et al. (2001).
  - First report of nuisance: 2006.
  - Discovery: August 2001, suburbs of Podgorica.
  - Pathway: road traffic from Albania and ferry traffic from Italy.
- Current situation
  - Surveillance: no surveillance, study, or control programmes are implemented for mosquitoes in general; however, *Aedes albopictus* is currently actively surveyed, but not on a regular basis.
  - Control: it seems that prior to 2007, no control measures were implemented.
  - Distribution: the species is spreading in all coastal areas; the current status of the population observed inland (Andrijevica) is not known.

Switzerland

- Introduction
  - Publications: Flacio et al. (2004); Wymann et al. (2008).
  - First report of nuisance: 2007.
  - Discovery: 2003, in ovitraps placed along major roads in southern Switzerland (Ticino).
  - Pathway: evidence of transport by road traffic from Italy.
- Current situation
  - Surveillance: regional surveillance and control programmes for mosquitoes were implemented by local authorities (cantons) in some areas; an active specific surveillance programme for *Aedes albopictus* was implemented in 2000 in southern Switzerland (canton Ticino); at the national level, passive surveillance was implemented in 2008.
  - Control: in Ticino, control measures have been applied since 2004.

  - Distribution: in Ticino, observations from 2004 to 2006 indicated regular introductions by road traffic from Italy, but also an efficient control of these populations; the species is currently well established in the Italian border area, and the number of positive sites as well as the size of the observed populations in Ticino increased dramatically in 2007, suggesting a continuing expansion of the species in that region; another focus was reported north of the Alps in autumn 2007, but to this date, neither its local establishment nor its spread has been reported.

Greece

- Introduction
  - First publication: Samanidou-Voyadjoglou et al. (2005).
  - First report of nuisance: people on Corfu reported mosquito nuisance in 2000–2001.
  - Discovery: 2003, Corfu and Igoumenidsa.
  - Pathway: ferry traffic from Albania and/or Italy.
- Current situation
  - Surveillance: regular regional surveillance and control programmes are implemented in a few regions, by public or private organisations and with the support of local authorities (prefectures); some specific active surveillance programmes for *Aedes albopictus* have existed since 2006 in Serres and Corfu prefectures, organised and funded by local authorities. However, the global information level is arguably scarce for the country.
  - Control: control measures are applied only in one case (Serres) where a general public mosquito control programme was established.
  - Distribution: the first case (Corfu, 2003) featured a homogenous population and spreads, for the second case (Igoumenidsa) no updated information is available, and the third case (Serres) can be considered an isolated focus; in the Serres area, the species is controlled within the framework of a general mosquito-control programme.

Spain

- Introduction
  - First publication: Aranda et al. (2006).
  - First report of nuisance: 2003, near Barcelona.
  - Discovery: 2004.
  - Pathway: probably by road traffic from Italy (no evidence for other pathway).
- Current situation
  - Surveillance: regular studies, surveillance and control programmes for mosquitoes are implemented in several regions, under local authorities; a specific active surveillance programme for *Aedes albopictus* based on a tyre trade survey was implemented in 2003–2004 but revealed no new cases; some active and passive surveillance measures were implemented in Cataluña, when the species was discovered in the area.
  - Control: control measures are applied only in the Barcelona area.
  - Distribution: the Barcelona/Tarragona area is now infested by a homogenous and spreading population; no updated information is available for the second focus in Alicante.

Croatia

- Introduction
  - First publication: Klobučar et al. (2006).
  - First report of nuisance: 2005.
  - Discovery: 2004, Zagreb.
  - Pathway: road traffic and ferry traffic from Italy, possibly also via used tyres imported from Italy.
- Current situation
  - Surveillance: regular mosquito surveillance and control programmes exist at regional levels (Osijek region and Zagreb); specific active surveillance programmes exist also in Zagreb and coastal regions, e.g. Istria (since 2000).
  - Control: public control programmes are now implemented in most of the infested coastal areas.
  - Distribution: the species is distributed as homogenous populations and is spreading in coastal areas; inland focus (Zagreb) was unchanged in 2007.

The Netherlands

- Introduction
  - First publication: Scholte et al. (2007).
  - First report of nuisance: 2005, in greenhouses.
  - Discovery: 2005.
  - Pathway: evidence for 'lucky bamboo' (*Dracaena sanderiana*) trade, from southern China.
- Current situation
  - Surveillance: regional studies of mosquito fauna are occasionally implemented; a specific surveillance programme for *Aedes albopictus* has existed since 2006.
  - Control: some control measures against *Aedes albopictus* are applied by greenhouse owners when nuisance is high.
  - Distribution: the species has been regularly observed in greenhouses (rarely outside) in three provinces (Zuid-Holland, Noord-Holland, Utrecht), and there is no evidence of larval breeding outside the greenhouses, therefore it cannot be considered established in the Netherlands.

Bosnia and Herzegovina

- Introduction
  - First publication: personal communication, Z. Lukac, in Petrić et al. (2006).
  - First report of nuisance: no updated information available.
  - Discovery: autumn 2005.
  - Pathway: probably road traffic from Italy.
- Current situation
  - Surveillance and control: a surveillance and control programme of mosquitoes exists only in one canton (Banja Luka).
  - Control: no updated information is available on control measures against *Aedes albopictus*.
  - Distribution: in 2005, the species was found in one focus (Banja Luka); no updated information is available on its establishment, its possible spread or its introduction in other regions.

Slovenia

- Introduction
  - First publication: Petrić et al. (2006).
  - First report of nuisance: 2005 ('Delo' newspaper, 7 September 2005).
  - Discovery/Observation: 2007.
  - Pathway: probably road traffic from Italy (no evidence for other pathway).
- Current situation
  - Surveillance: no surveillance, study, or control programmes are implemented for mosquitoes in general; no specific surveillance for *Aedes albopictus* exists but a study was conducted in 2007 in the Primorska region.
  - Control: no control programme for *Aedes albopictus* exists.
  - Distribution: the species is present in two foci, in the Primorska region where the population is homogenous and spreading, and in Ljubljana, as an isolated focus reported in 2007.

Monaco

- Introduction
  - *Aedes albopictus* was observed for the first time in Monaco in 2006 (data not yet published: F. Schaffner, personal communication); first complaints about nuisance were registered in 2007. Introduction and establishment occurred when the French Riviera became infested, due to transport by road traffic from surrounding areas in France or directly from Italy.
- Current situation
  - Surveillance and control: a regular national mosquito control programme against *Culex pipiens* is operated by a private company in accordance with health authorities; no specific surveillance or control programme for *Aedes albopictus* exists.
  - Distribution: a homogenous population is present in Monaco, just as in the surrounding French areas.

Germany

- Introduction
  - First publication: Pluskota et al. (2008).
  - First report of nuisance: no report to date.
  - Discovery: autumn 2007, in ovitraps on a motorway parking area.
  - Pathway: evidence for road traffic from Italy and through Switzerland.
- Current situation
  - Surveillance: regular studies, surveillance and control programmes for mosquitoes are implemented in a few areas, under the auspices of local authorities; a specific active surveillance programme for *Aedes albopictus* has also been implemented since 2005 in south-western Germany (Hessen, Rheinland-Pfalz, and Baden-Württemberg).
  - Control: specific control measures were scheduled to start in 2008.
  - Distribution: the species was observed in one focus, a motorway service area located in Baden-Württemberg; no local establishment and spread has been reported so far, which mirrors the situation in Switzerland (north of the Alps).

San Marino

- Introduction
  - *Aedes albopictus* was confirmed as present in 2007 in San Marino by experts contacted for this work (data not yet published: R. Mignani, personal communication). Introduction is most probably due to transport by road traffic from infested surrounding areas in Italy.
- Current situation
  - Surveillance and control: no surveillance, study, or control programmes are implemented for mosquitoes in general; no specific surveillance or control programme for *Aedes albopictus* exists.
  - Distribution: a homogenous population is present in San Marino, just as in the surrounding Italian areas.

Vatican City

- Introduction
  - *Aedes albopictus* presence was confirmed in Vatican City in 2007 by experts contacted for this work (data not yet published: C. Venturelli, personal communication). Introduction is most probably due to transport by road traffic from infested surrounding areas in Italy, i.e. the city of Rome. As this city has been infested since 1997, the presence of the mosquito in Vatican City probably dates back to the same time period.
- Current situation
  - Surveillance and control: no surveillance, study, or control programmes are implemented for mosquitoes in general; no specific surveillance or control programme for *Aedes albopictus* exists.
  - Distribution: a homogenous population is present in Vatican City, just as in Rome.

4.2 Random Forests outputs

The backward stepwise Random Forest retained four variables out of the 57 predictors. The four predictors are all related to temperature: the maximum night-time land surface temperature (LST), the mean annual daytime LST, the minimum daytime LST, and the second amplitude of the daytime temperature. The effect of the maximum night-time LST and the minimum daytime LST was the strongest (Table 1). It is interesting to note that despite the inclusion of rainfall, the model did not select this predictor.

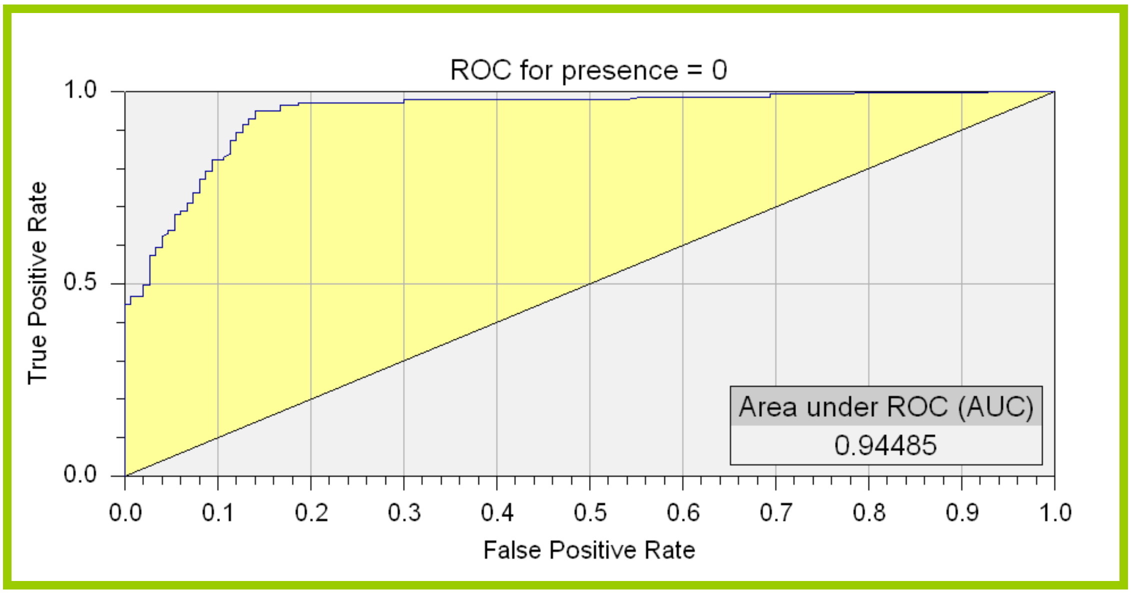
Table 1. Selected predictor variables using a backward stepwise Random Forest model

Variable	Variable importance
Max nightLST	100.00
Mean annual dayLST	98.52
Ampl2 dayLST	73.16
Min dayLST	42.92

Based on the out-of-bag procedure, the following confusion matrix is obtained:

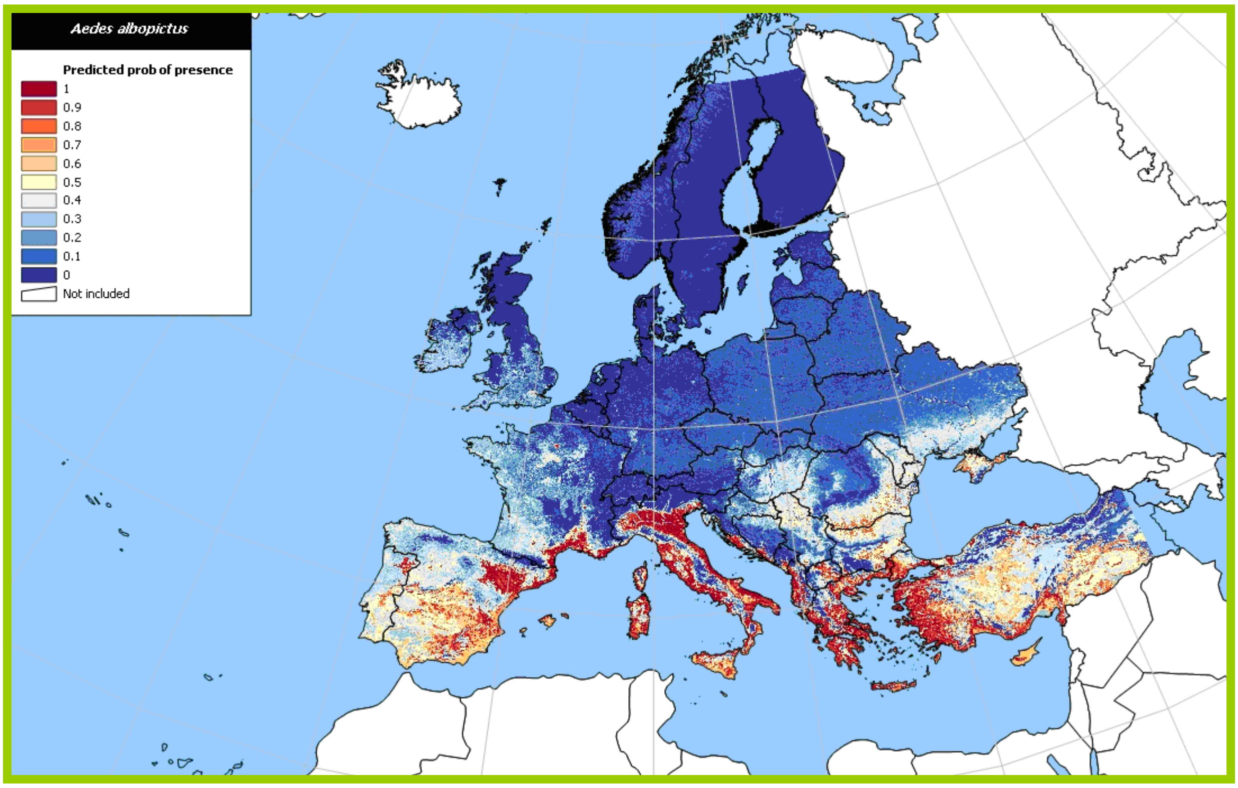
Observed	Predicted	
	Presence	Absence
Presence	129	12
Absence	19	131

The corresponding ROC curve is shown below:



As expected from the accuracy measures, the Random Forest model closely reflects the current distribution of *Aedes albopictus* depicted in Figures 1–3 (Annex) and predicts the mosquito's further invasion in the Mediterranean basin both towards the east and the west.

Figure iv. East and westward invasion of Aedes albopictus in the Mediterranean basin



In Italy, suitability is confirmed for the southern part and Sicily where observed data at the finest administrative level are currently rather weak (Figure 3). Towards the east, suitability is predicted for most of Greece and in Turkey, with the exception of the highlands. Currently, no data are available from most areas of both countries; presence has been reported in Serres (north-eastern Greece). Absence was reported for Cannakale, Balikesin, Aydin and Antalya (coastal continental Turkey). Given the mosquito's spread — it is known to travel with vehicles along road networks — these results may suggest that more time is needed for the mosquito to reach these areas.

Towards the west, the suitability for *Aedes albopictus* is confirmed for Mediterranean France and predicted for large parts of the Iberian peninsula, while the part adjacent to the Atlantic and in the northern third of Spain are predicted as unsuitable. Very little data are currently available from this area and more are needed to clarify this. As for Turkey, the mosquito may need more time to invade larger parts of the peninsula. But eco-climatic conditions along the Atlantic may be too different from the Mediterranean coastal area and thus either prevent the mosquito's long-term establishment or, since the model is lacking training data from that area, falsely suggest unsuitability.

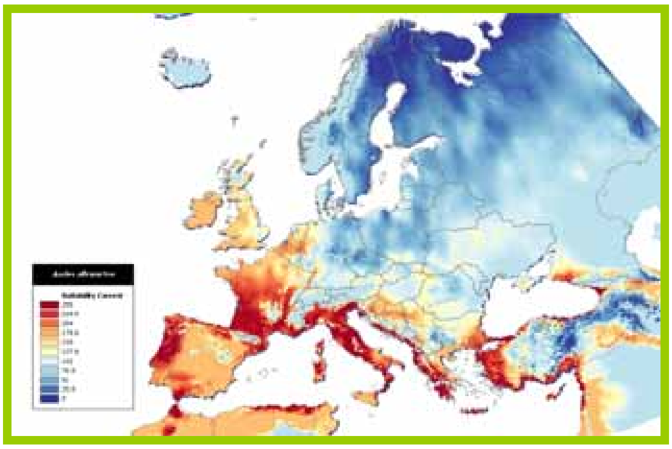
The same may be true regarding the potential northern spread of the mosquito. Given the current presence data centred on the Mediterranean, no suitability is predicted further north. Yet we know that the mosquito is currently actively expanding and has not yet reached its northern limit (see also section 3.5). It is therefore interesting to note that the model predicts probabilities of 0.2 to 0.4 in large parts of northern Spain, France, the UK and Ireland. The same is true for large parts of the Balkan, as far as Hungary and along the Black Sea. Higher suitability rates are predicted in the Danube valley. Finally, and interestingly, large cities such as Paris and London are highlighted on the risk map because all variables that drive the model are temperature-related, and temperatures in these megacities are several degrees higher than in surrounding areas.

It may be concluded that the model is an excellent tool for describing the mosquito's current distribution in the Mediterranean. It also predicts the mosquito's spread in areas similar to the areas where mosquito presence was observed along an east-west axis. Little can be said about the mosquito's potential spread to the more northern parts of Europe and the Atlantic coastal regions of Spain — areas that differ substantially from the current presence areas. The model successfully highlights areas that are strongly recommended for monitoring the spread of *Aedes albopictus* in the Mediterranean. At current, these areas are mostly predicted as suitable, but little or no data are available.

4.3 MCDA outputs

The result of the MCDA model is given as Figure 5 (Annex). A reduced-sized copy is given below.

Figure v. Results of MCDA model



The areas of potential suitability are depicted in red. All Mediterranean countries show, as a rule, higher suitability in the coastal areas and lower suitability in mountainous areas. Italy appears most suitable. On the Iberian Peninsula, the north-western part appears more suitable than the central and eastern parts. The coastal parts of Greece, Turkey and the Balkan countries also appear very suitable. Most of southern and western France are highly suitable. Farther north, the northern (lower) part of Belgium and the Netherlands, as well as large parts of UK and Ireland, are also suitable, although to a lesser extent.

When comparing the MCDA output to the GARP output produced by Benedict et al. (2007), striking similarities become apparent despite the fact that the modelling techniques are very different. MCDA is an expert-driven approach to model the potential limits of a still expanding species which is independent from a, per definition, incomplete observed dataset. GARP modelling on the other hand is based on the currently established niche, as determined by the occurrence dataset.

An additional advantage of using MCDA instead of GARP is its easy application: using GARP requires a training dataset of occurrence and must be set up with multiple parameters (crossover probability, mutation probability, selection strategy, number of generations, convergence criterion, etc.). In this case GARP was executed for ten runs which were then combined, adding to its complexity.

The MCDA model on the other hand is straightforward to use through a linear (or multiplicative) combination of a set of identified predictor variables. MCDA also offers the additional advantage of preparing for assessing the impact of future predicted temperatures and rainfall on the potential distribution of *Aedes albopictus* (see part 3.6).

4.4 Potential activity period

As the onset of diapause in autumn and egg hatching in spring are dictated by environmental variables (climate and photoperiod), the developed GIS model predicts the number of weeks of activity of *Aedes albopictus* (Figure 6, Annex). The model outputs can be used to determine whether a) the mosquito would be active long enough to become established in a new location, and b) where there might be prolonged activity, thereby acting as a surrogate for mosquito abundance.

The map in Figure 6 shows that most of Europe is suitable for the development of *Aedes albopictus* for at least part of the year. This does not mean, however, that introduced populations could overwinter to the following year; these criteria are assessed in other model outputs.

4.5 Comparison between Europe, USA and Japan

For Japan, Kobayashi et al. (2002) reported that in areas where mosquito infestation was confirmed, more than 186 days with temperatures exceeding 11° C were recorded, and the accumulated temperature exceeded 1350 degree days.

In the US, 91 % of the counties where *Aedes albopictus* is present have a minimum annual mean temperature above 11° C; 96 % of these counties report an average annual mean temperature exceeding 11° C, and 98 % have a maximum annual mean temperature exceeding 11° C.

In Europe, a similar pattern is encountered: 81 % of the municipalities where the vector was found have a minimum annual mean temperature above 11° C, 94 % report an annual mean temperature higher than 11° C, and 99 % have a maximum annual mean temperature exceeding 11° C. Interestingly, the only municipalities where the maximum annual mean temperature is lower than the threshold are municipalities in the Netherlands where *Aedes albopictus* is only confirmed in greenhouses and has never been reported outside.

Figure vi. Lowest (left) and highest (right) recorded mean temperatures in US counties with confirmed infestations of *Aedes albopictus*

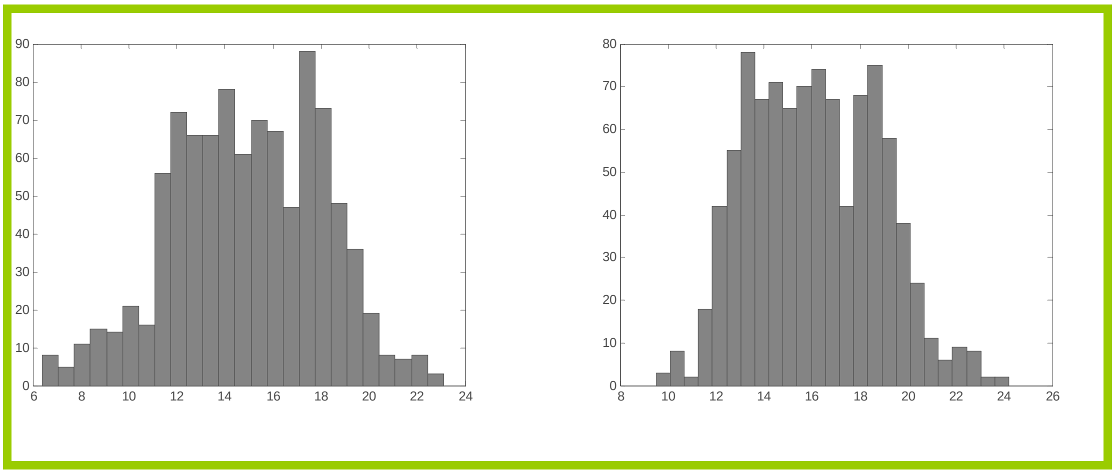
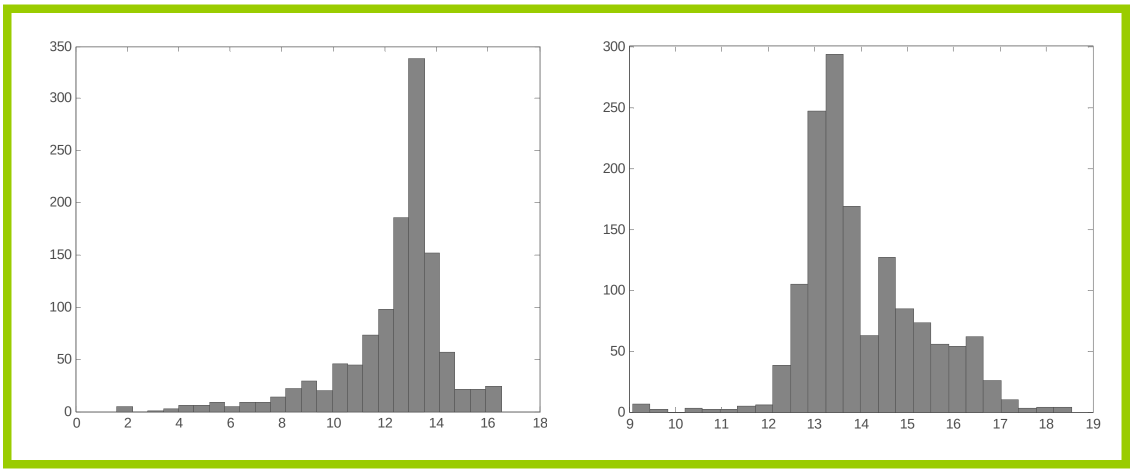


Figure vii. Lowest (left) and highest (right) recorded mean temperatures in European municipalities with confirmed infestations of *Aedes albopictus*



When determining the number of days per city where temperatures exceed 11° C, the results show that 89 % of the infested US counties have more than 186 days above this limit (Figure iv). The lowest number of days reported for cities located in a county flagged with *Aedes albopictus* presence is 157. The accumulated temperature (degree days) > 1320 DD per year. For Europe, the lowest number of degree days is 203 (Figure v), and the accumulated temperature is > 1511 DD per year.

The maps below (Figure vi, USA; Figure vii, Europe) show the recorded presence of *Aedes albopictus* in counties or municipalities, respectively. Temperature records are superimposed over major cities when daily temperature data were available; for each of these cities, the number of days above 11° C is given.

Figure viii. Number of days in US cities with temperatures exceeding 11° C.

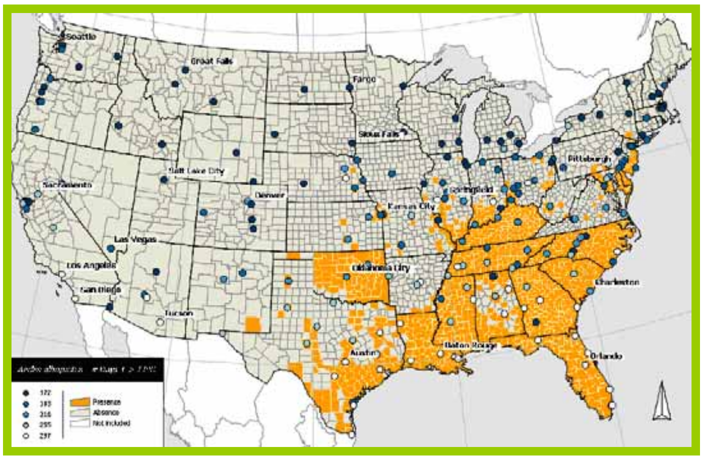
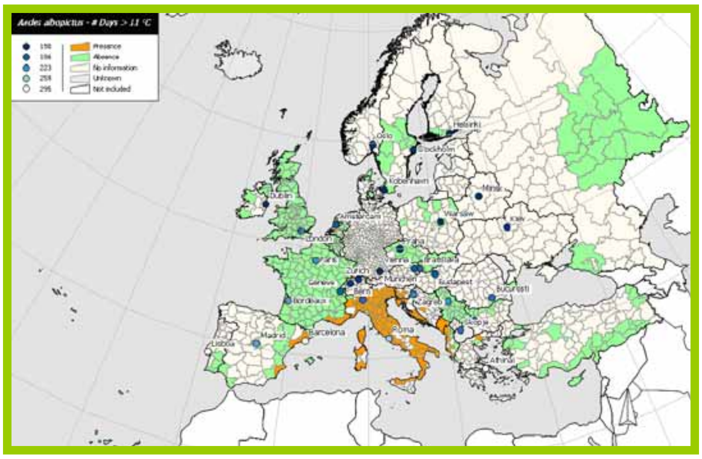


Figure ix. Number of days in European cities with temperatures exceeding 11° C



4.6 Impact of climate change

The results of the MCDA models using predicted temperature and rainfall data according to minimal and maximum impact climate change scenarios are given as Figure 7a-d (Annex).

For the minimal impact short-term MCDA output, IPCC models and scenarios causing the least impact on climate change were used. The output shows the projected effect of these changes on the potential distribution of *Aedes albopictus* in 2010. When compared to the current situation (Figure 5), most changes are anticipated in two areas: in Central Europe (including the southernmost parts of Sweden), and in the Balkans.

For the minimal impact long-term output providing projections for 2030, a shift in changes is observed. While the 'Central European zone' described above now reaches as far as the Baltic states and covers large parts of southern Sweden, the 'Balkan zone' does not expand any farther and even shrinks, with parts of Romania and Bulgaria becoming unsuitable for *Aedes albopictus*.

For the maximum impact short-term output, IPCC models and scenarios causing maximum impact on climate change were used, and projections are shown in the same time frame. For both the short- and the long-term output, changes are similar and show a significant further eastward extension, suggesting that most of Europe would become favourable to *Aedes albopictus* should these scenarios prove true.

5 Discussion

The observed distribution database and the extracted maps that are part of this report meet the goals that were set by ECDC. Based on quality-controlled data, a series of maps (Figures 1–3 and other maps not shown here) can be extracted, describing the current distribution of viable populations and historical presence of *Aedes albopictus* in continental Europe as per January 2008. The database also includes information on vector control and surveillance activities for each country. Areas where data are missing were also identified. ECDC now owns a geo-referenced database which can be regularly updated by drawing on the resources provided by an established pan-European network of specialists.

The second objective of this report was to model the risk of establishment of *Aedes albopictus* and its spread in Europe. This issue was addressed from various angles:

- a spatial model based on available data on presence/absence;
- a multi-criteria decision support analysis based on expert knowledge, i.e. an expert meeting on *Aedes albopictus* in Paris, organised by ECDC;
- a GIS potential-activity model based on biological observations of diapause, adult survival in winter, and egg hatching in spring; and
- a comparison with the distribution of *Aedes albopictus* in the USA, the suspected country of origin of strain of *Aedes albopictus* established in Europe.

Unlike tropical strains, only temperate strains of *Aedes albopictus* overwinter as eggs, an evolved feature that has facilitated their spread to more northerly latitudes. During the shortening daylight hours in late summer/early autumn, the reduced photoperiod stimulates the females to produce eggs that enter facultative diapause (Estrada-Franco & Craig 1995). These eggs are able to resist hatching stimuli until the following spring and remain in a state of reduced morphogenesis as fully formed first instar larvae, exhibiting increased resistance to environmental extremes. Although the diapause is expressed in the egg stage, it is the adults and pupae that are the photoperiodically sensitive stages (Wang 1966, Imai & Maeda 1976, Mori et al. 1981).

It is important to note that the Italian *Aedes albopictus* strains are closely related to the strains found in the USA and Japan (Urbanelli et al. 2000) and are known to be diapause-competent populations (Toma et al. 2003). It is likely that the populations in adjacent or surrounding countries are closely related to the Italian strains, although molecular studies confirming this hypothesis are still lacking. The *Aedes albopictus* strains that are regularly imported into the Netherlands through the 'lucky bamboo' trade derive directly from the southern (sub)tropical areas of China (mainly Guangdong province); it is hypothesised that these populations are not diapause-competent strains and potential establishment of these populations is probably less likely in temperate areas (Takumi et al., 2008). It should be stressed that establishment process of these *Aedes albopictus* strains is probably very different from the ones purportedly introduced from the US.

The GIS potential activity model (Figure 6) clearly shows that most parts of Europe are suitable to permit summer development (not necessarily winter survival) of the *Aedes albopictus* strains currently established in the Mediterranean. There appears to be no reason to rule out a spread comparable to the one observed in the USA.

The same rapid evolution that facilitated its adaptation and survival in North America and Europe makes it a distinct possibility that the mosquito has the potential to further adapt to local climates and photoperiod thresholds. While no adaptation was necessary for the mosquito to become established, its ability to adapt and evolve will undoubtedly contribute to increase its foothold on the continent. Consequently, the models developed for this report will have to be updated iteratively, as the mosquito adapts to its surroundings.

An example of *Aedes albopictus'* ability to adapt is the fact that adult females were reported as overwintering in Rome. A relatively large proportion of ovitraps that were continuously monitored in Rome were found containing eggs during the winter months, indirectly proving adult female activity during winter (R. Romi, personal communication).

While the potential-activity GIS model (Figure 6) depicts most of Europe as being receptive for summer development and potential establishment of *Aedes albopictus* in Europe, a more nuanced picture is presented by the Random Forest model (Figure 4) and the MCDA (Figure 5) outputs. Both approaches consider aspects such as climatic limitations in winter.

Based on the outcome of the Random Forest model (Figure 4) discussed under '3 Methodology' (Task 2), it may be concluded that the model is an excellent tool for describing the current distribution around the Mediterranean basin. The model also predicts the mosquito's spread along an east-west axis in areas similar to those areas where presence is currently observed. Little can be said about the mosquito's potential spread to the more northern parts of Europe and the Atlantic coastal regions of Spain, as these areas differ substantially from the current areas of presence. The model thus successfully highlights areas where monitoring of *Aedes albopictus* is urgently recommended, i.e. along the Mediterranean coastline. These areas are currently predicted as suitable, but little or no data are available for these regions — a fact that further stresses the need for continuous monitoring.

Therefore, a second type of approach that is completely unrelated to observed presence/absence data was used. This approach relies on expert advice in order to define climatic thresholds for presence and absence. These thresholds are then converted to fuzzy membership functions (i.e. avoiding a sharp cut between favourable and unfavourable conditions), as depicted in the graphs in Figure 5. Finally, these functions are applied to the relevant climatic data layers and combined.

The results (Figure 5) are complementary to the Random Forest model (Figure 4). While the latter shows current high-priority areas monitored for short-term spread of existing *Aedes albopictus* populations, the former offers a medium-term perspective and highlights areas of potential infestation.

The results of this report are supported when comparing the different spreads of *Aedes albopictus* in the USA, Europe and Japan. The annual mean temperatures correspond well between the USA, Europe and Japan. The criterion of an annual mean temperature of 11° C seems to fit well with the overall observed distribution of the temperate strain of *Aedes albopictus*. The number of DD days is similar to the 1350 DD days for Japan as stated by Kobayashi et al. (2002).

If we maintain that the 11° C threshold is an important parameter, it can be assumed that the spread of *Aedes albopictus* may continue in the US along the Pacific Coast, while the northern spread might be more limited. In Europe, the distribution above 45° latitude might cover the whole of France, parts of the UK and Belgium. Below 45° latitude, the distribution covers the Mediterranean basin.

While a single parameter will never delineate distribution of a vector on a local scale, using the annual mean temperature in combination with degree days seems to indicate which areas might be more at risk on a regional level.

When combining the output of the three models and the other information provided above, one may arrive at an informed opinion on the risk of establishment and spread of *Aedes albopictus* in Europe:

- Only a temperate strain capable of diapause may become established and spread from one season to the next. No climate change is required for a temperate strain of *Aedes albopictus* to become established in Europe.
- *Aedes albopictus* already has established a foothold in the Mediterranean and is likely to spread further northwards — as shown by the MCDA output — in a way comparable to the one observed in the US. In doing so, the mosquito may further adapt, as has previously been observed, and increase its potential range.
- In theory, most of Europe offers, for at least part of the year, suitable conditions for *Aedes albopictus* to become established, long-term sustained establishment and spread has only been observed in the Mediterranean. This does not rule out future establishment, but it further emphasises that the major threat for Europe emanates from the spread of Mediterranean populations.

Finally, an analysis of the potential impact that climate change could have on the spread of the mosquito was provided. The analysis confirms — using both minimal and maximum impact ICCP models/scenarios — that an increase in areas potentially suitable for *Aedes albopictus* will be observed.

Given the above, it can be concluded that the temperate strains of *Aedes albopictus* are here to stay — and that they will spread. In addition, new populations may become established in other parts of Europe. The latter is more likely to occur in areas shown as favourable by MCDA, and these areas may further extend to the east in the future.

It is important to note that this report focuses on the presence, the spread, and the risk of establishment of *Aedes albopictus*. The report's analysis and conclusions do not apply to the risk of transmitting exotic viruses, nor can one extrapolate from them to assess any such risk. Analysing this risk would require a significant number of additional datasets, e.g. vector capacity in the given eco-climatic settings.

The results and conclusions shown in this report are a significant improvement over the existing state-of-the-art in *Aedes albopictus* distribution research.

6 Recommendations

Based on the above results, it is recommended:

- to establish a permanent database at ECDC, disseminate it, and further develop state-of-the-art tools to model *Aedes albopictus* distribution and the risk of its establishment and spread;
- to maintain and further build on the established expert network to keep the database regularly updated;
- to improve and complement the entomological database:
  - on general mosquito surveillance or studies on states for which no information was available: Belarus, Iceland, Macedonia, Malta, Moldova, and Ukraine;
  - on presence or absence of *Aedes albopictus* in suspected areas (e.g. certain regions in Italy) and states (Hungary), and in countries neighbouring infested areas (see Figure 1): Austria, Bulgaria, Kosovo, Macedonia, Malta, and on its establishment and possible spread in Bosnia and Herzegovina and in localised foci north of the Alps;
  - on presence or absence of *Aedes albopictus* along transects, from sea level to higher altitude (following main transport routes) in long-infested areas (Italy or Albania) in order to validate climate factors limiting its establishment;
- to survey the possible introduction and establishment of *Aedes albopictus* in priority countries that offer no or very limited data on mosquito fauna and that are described as 'high'-risk countries for its establishment (see Figures 4-5): Cyprus, Bulgaria, Macedonia, Portugal, southern Russia, Turkey;
- to study the genetic homogeneity/heterogeneity of European mosquito populations as this would help to understand introduction pathways and assess evolution/adaptation of populations;
- to survey the introduction, possible establishment and spread of *Aedes aegypti* and other exotic potential vectors;
- to promote research on the development of adapted control measures to eradicate newly established colonies and to prevent the mosquito's spread;
- to promote research assessing the vector capacity of European *Aedes albopictus* strains with regard to exotic viruses.

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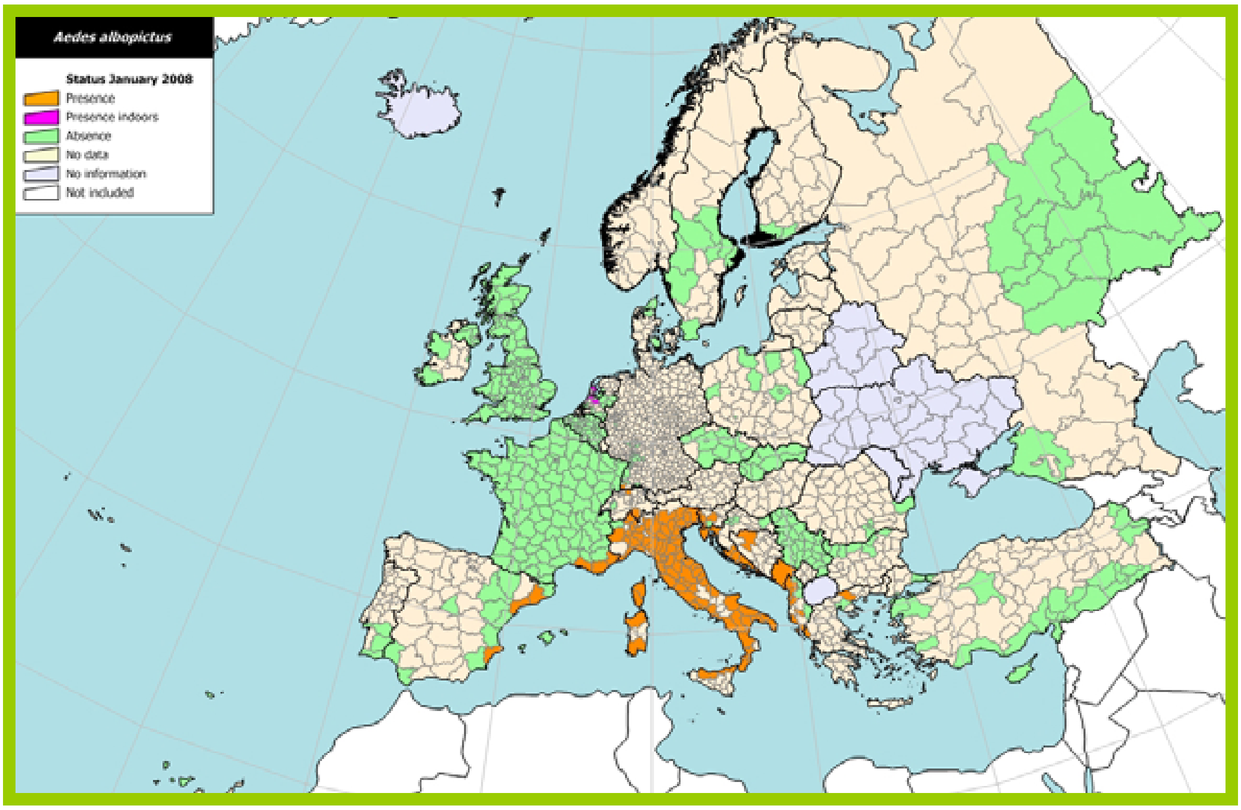
Annex 1: Maps

Map 1. Current distribution of *Aedes albopictus* in Europe, January 2008

Figure 1. Current distribution of *Aedes albopictus* in Europe



The map shows the current distribution of *Aedes albopictus* at 'regional' administrative levels (NUTS3 or LAU1; 52 states, microstates, or dependencies; members of the European Union, and/or located in Europe or geographically close to it). Regions are colour-coded:

- orange: the species was observed at least in one municipality;
- purple: the species was only observed indoors (in greenhouses);
- green: surveys and studies on mosquitoes were conducted during the last five years (2003–2007) and no specimen of *Aedes albopictus* was reported;
- pale yellow: no recent (last five years) data on mosquito fauna is available to local scientists (see list of network contacts in the report);
- grey: no information is available on the existence of studies on mosquito fauna;
- white: countries not included in this study.

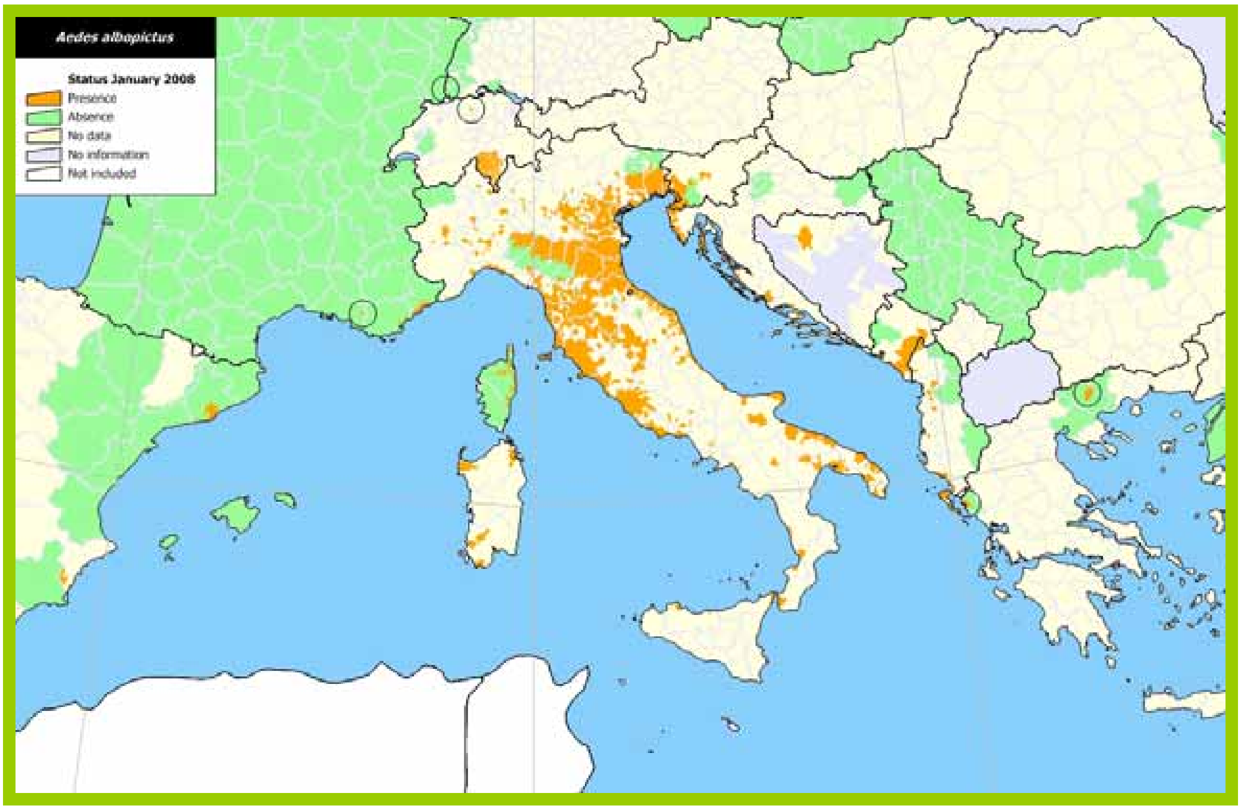
Only confirmed data were used, most of them provided by experts in the respective countries.

In 2007, *Aedes albopictus* was observed at least once in 15 states. The species has homogenous populations, generally associated with complaints about nuisance biting, and could be considered as spreading in 11 countries and micro-states: Albania, Croatia, France, Greece, Monaco, Montenegro, Italy, San Marino, Slovenia, Spain and Vatican City. Isolated foci exist in these countries, as well as in others. The species has been regularly introduced into southern Switzerland, and sustained control measures prevented its establishment and spread until 2006, but recent data suggest a continuing spread. It is present in isolated foci in Bosnia and Herzegovina, but information is too scarce to confirm this with more accuracy. Despite the fact that the mosquito has been regularly introduced, it cannot be considered as established. It is regularly (re-)introduced in the Netherlands but it has not yet been observed spreading outside greenhouses, therefore it cannot be considered as established in this country. It was observed once in 2007 in Germany and in Switzerland (north of the Alps), but its establishment in these regions is not yet proven. It was observed also in Belgium in 2000, but the species is no longer present.

Information on presence/absence varies in quality, and ranges from national and regular surveillance to a total absence of surveillance or studies; green, white and grey indicate information quality.

Map 2. Current distribution of *Aedes albopictus* in the Mediterranean basin, January 2008

Figure 2. Current distribution of *Aedes albopictus* in the Mediterranean basin



The map shows the current distribution of *Aedes albopictus* in the Mediterranean basin, at 'municipality' level (LAU2) for data on presence, and at 'regional' administrative level (NUTS3 or LAU1) for other data. Municipalities and regions were colour-coded accordingly:

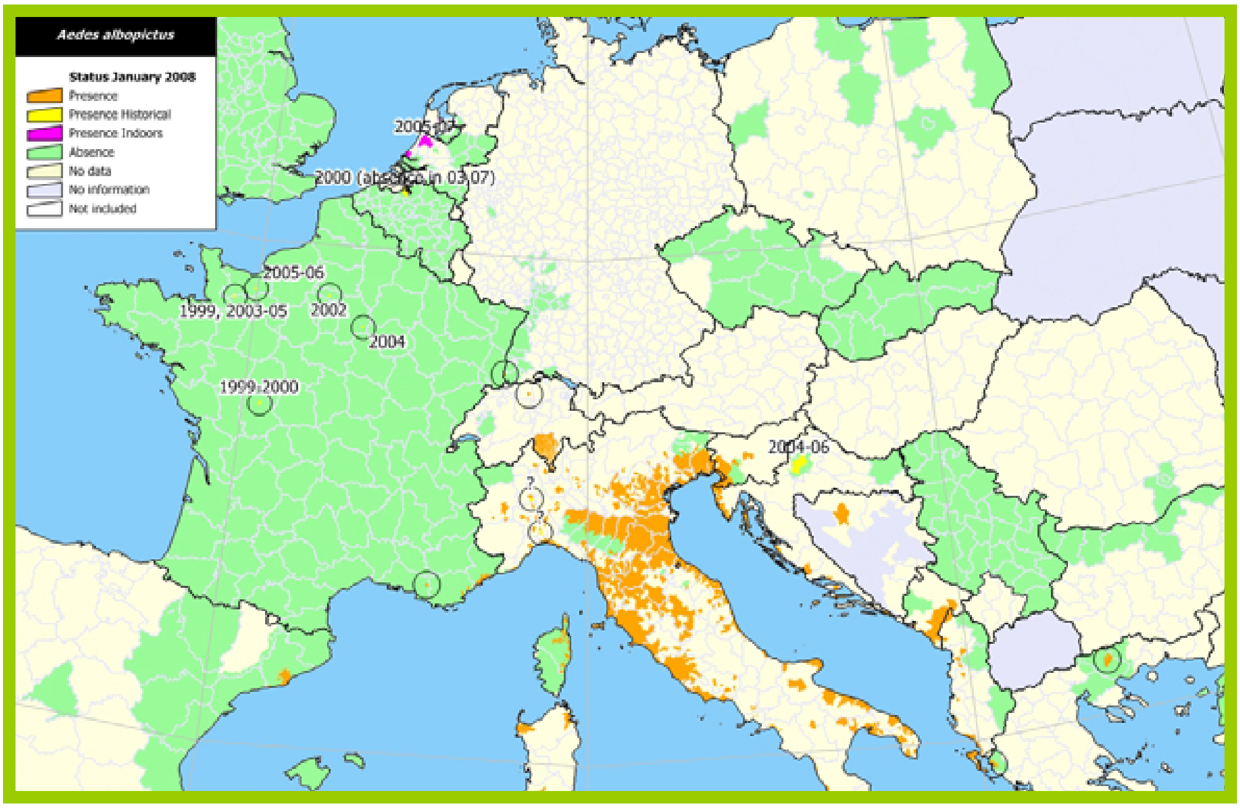
- orange: the species was observed in 2007;
- green: surveys and studies on mosquitoes were conducted during the last five years (2003–2007) and no specimen of *Aedes albopictus* was reported;
- pale yellow: no recent (last five years) data on mosquito fauna is available to local scientists (see list of network contacts in the report);
- grey: no information is available on the existence of studies on mosquito fauna;
- white: countries not included in this study.

Data were provided by experts in the different countries. Circles indicate small localised foci.

Information on presence/absence varies in quality; green, white and grey indicate information quality. Twelve countries implemented specific surveillance for *Aedes albopictus* and other exotic mosquitoes during the last five years. For some countries, this national and regular surveillance was either active (i.e. Belgium, France, the Netherlands) or passive (i.e. United Kingdom, Serbia). For Albania, available data show a scattered distribution of *Aedes albopictus*, due to scattered surveillance, as only a few locations were investigated. The species is most probably present as homogenous populations in all coastal areas, from the seaside up to altitudes of 690/700 m above sea level. For Italy, the scattered distribution is also partly due to a lack of information, especially for southern areas where the species most probably infests coastal areas. However, almost all areas that are located in mountainous regions above 500 meters above sea level appear to be free of *Aedes albopictus*. Because of more recent introduction, infested areas in other countries appear to be limited in size, but information is also scarce for some of them (i.e. Bosnia and Herzegovina, Greece). Foci observed in Switzerland and Germany (north of the Alps) are recent (2007), and establishment of the species in these regions is not yet proven. Surveillance should be implemented in countries neighbouring colonised areas, e.g. in Austria, Bulgaria, Kosovo, Macedonia, and Malta.

Map 3. Current and historical distribution of *Aedes albopictus* in central Europe, January 2008

Figure 3. Current and historical distribution of *Aedes albopictus* in Central Europe



The map shows the current and historically known distribution of *Aedes albopictus* in central Europe, at 'municipality' level (LAU2) for data on presence, and at 'regional' administrative level (NUTS3 or LAU1) for other data. Municipalities and regions were colour-coded accordingly:

- orange: the species was observed in 2007;
- purple: the species was only observed indoors (in greenhouses) and, despite it being introduced regularly, it cannot be considered as established;
- dark yellow: the species was observed in the past but it is no longer present;
- green: surveys and studies on mosquitoes were conducted during the last five years (2003–2007) and no specimen of *Aedes albopictus* was reported;
- pale yellow: no recent (last five years) data on mosquito fauna is available to local scientists (see list of network contacts in the report);
- grey: no information is available on the existence of studies on mosquito fauna;
- white: countries not included in this study.

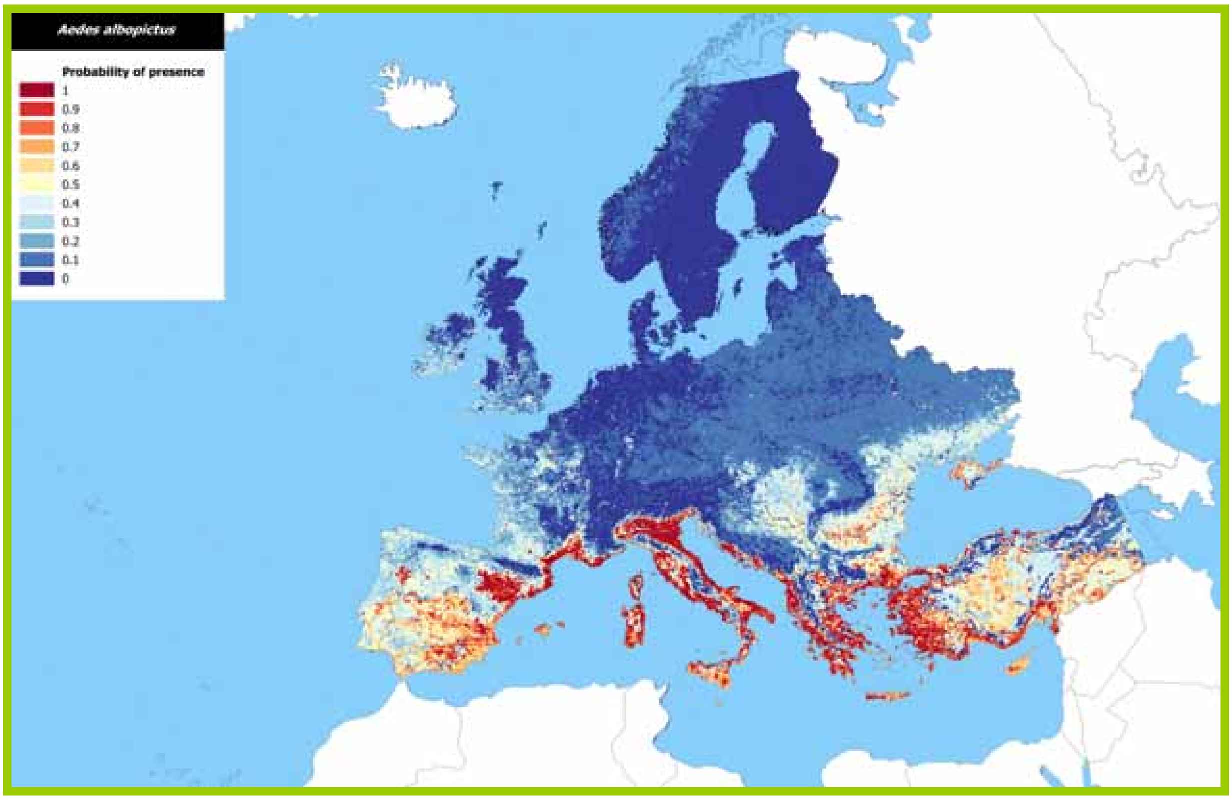
Data were provided by experts in the respective countries. Circles help to localise small foci; those with date labels are historical.

Information on presence/absence of the mosquito varies in quality, and ranges from national and regular surveillance (i.e. Belgium, France) to a total absence of surveillance or studies (i.e. Austria, Macedonia, Hungary); green, white and grey indicate information quality.

Scattered distribution data outlined in white indicate scattered information; the species has most probably infested all coastal areas in Albania and Italy. However, areas that are located in mountainous areas above 700 meters above sea level seem to be free of *Aedes albopictus*. Foci observed in Switzerland and Germany (north of the Alps) are recent (2007), and establishment of the species in these regions is not yet proven. It is regularly (re)introduced to the Netherlands, but it has not yet been observed spreading outside greenhouses and can therefore not be considered as established. *Aedes albopictus* was eradicated, albeit temporarily, from some of the introduction foci in Croatia, France, Italy, and Switzerland, thanks to preventive surveillance and rapid application of control measures. It has not become established in Belgium after introduction. Surveillance should be implemented in countries neighbouring colonised areas, like Austria, Bulgaria, Kosovo, Macedonia, and Malta, as well as Hungary, where it was suspected to have been introduced in 2001.

Map 4. Distribution risk map for *Aedes albopictus*, statistical model

Figure 4. Distribution risk map for *Aedes albopictus*, statistical model



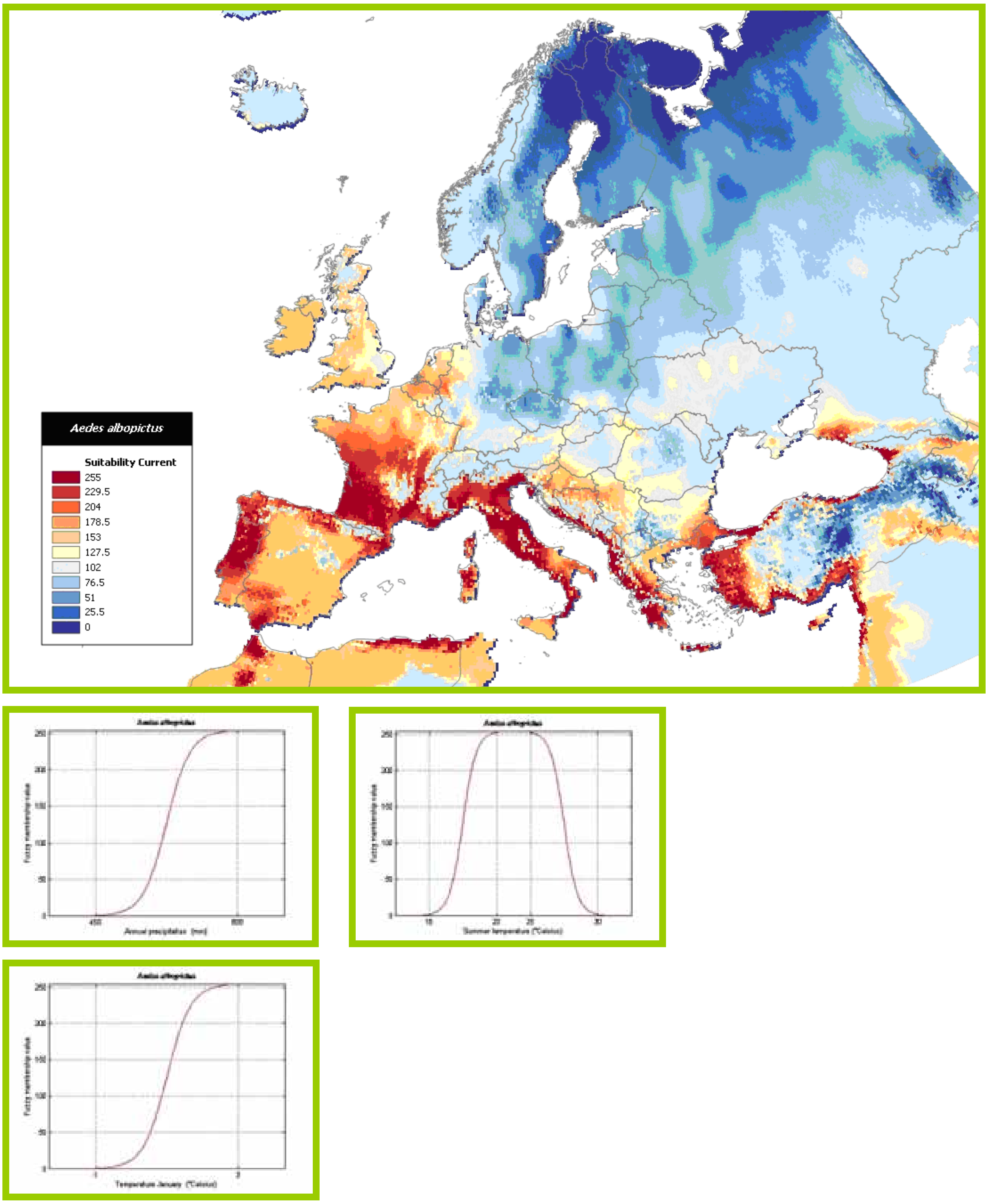
The backward stepwise Random Forest retained four variables out of the 57 predictors. All are related to temperature: the maximum night-time land surface temperature (LST), the mean annual daytime LST, the minimum daytime LST, and the second amplitude of the daytime temperature. It is interesting to note that although rainfall was included, the model did not select this predictor.

The Random Forest model closely reflects the current distribution of *Aedes albopictus* as depicted in Figures 1–3 and predicts the further invasion of the Mediterranean basin, both eastward and westward.

Based on results discussed in this report, it may be concluded that the model is an excellent tool for describing the current distribution around the Mediterranean basin. The model also predicts the mosquito's spread along an east-west axis in areas similar to those areas where presence is currently observed. Little can be said about the mosquito's potential spread to the more northern parts of Europe and the Atlantic coastal regions of Spain, as these areas differ substantially from the current areas of presence. The model thus successfully highlights areas where monitoring of *Aedes albopictus* is urgently recommended, i.e. along the Mediterranean coastline. These areas are currently predicted as suitable, but little or no data are available for these regions — a fact that further stresses the need for continuous monitoring.

Map 5. Distribution risk map for *Aedes albopictus*, MCDA model

Figure 5. Distribution risk map for *Aedes albopictus*, MCDA model



Suitability map for the presence of *Aedes albopictus* using multi-criteria decision analysis. Using expert advice, membership functions are determined that relate suitability to predictor variables, annual precipitation, summer temperature and temperature in January. For annual precipitation, suitability is zero when rainfall is lower than 450 mm, and maximum (255) when precipitation is higher than 800 mm; for summer temperature, the suitability is zero when temperatures are lower than 15° C and higher than 30° C, and maximum between 20° C and 25° C; for January temperature, the suitability is zero when temperatures are lower than -1° C, and maximum when temperatures are higher than 3° C.

The individual variables are added using a linear combination and result in the final suitability map. Colours show the suitability levels, from the less suitable areas (dark blue) to the most suitable areas (dark red).

All Mediterranean countries appear to be suitable for *Aedes albopictus*, with higher suitability in coastal areas and lower suitability in mountainous areas. Italy appears the most suitable. The north-western part of the Iberian Peninsula appears more suitable than the central and eastern part. Greece, Turkey, and the coastal part of the Balkan countries also appear to be very suitable. Most of southern and western France are highly suitable. The northern (lower) part of Belgium and the Netherlands as well as large parts of the UK and Ireland are also suitable, although to a lesser extent. With regard to areas that pose a high risk for establishment of mosquito populations, surveillance of *Aedes albopictus* should be implemented in Cyprus, Bulgaria, Macedonia, Portugal, Southern Russia, and Turkey. Our analysis and conclusions do not apply to the risk of transmitting exotic viruses, nor can one extrapolate from this report to assess any such risk.

Map 6. Potential weeks of activity of *Aedes albopictus* in Europe

Spring hatching to adult die-off

Figure 6. **Potential weeks of activity of *Aedes albopictus* in Europe — spring hatching to adult die-off**

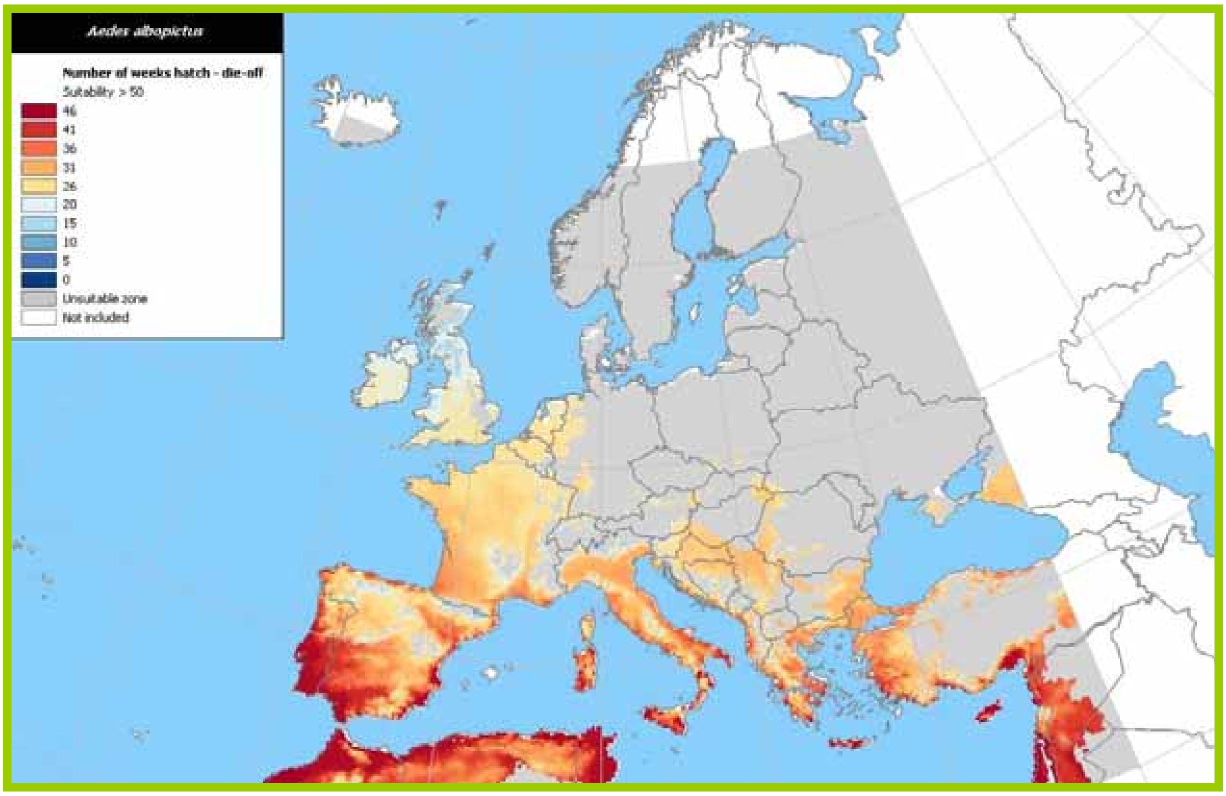


Figure 6 depicts the predicted number of weeks between hatching of overwintered eggs in spring (in response to 11.25 hrs of daylight, 10.5° C mean temperature) and the critical temperature threshold of 9.5° C in autumn that is considered crucial for adult survival. Colours indicate the areas with their potential number of weeks of activity, from the lowest number (white) to the highest (brown).

Throughout much of Europe, more than 23 weeks are predicted to elapse between egg hatching and adult die-off in autumn. Assuming that immature development takes 2–4 weeks, this constitutes > 20 weeks of adult activity, increasing to > 40 weeks in southern areas, depending on availability of surface water for breeding. Prolonged activity is possible in north-east Europe, but factors that limit overwintering capabilities are likely and were therefore removed from this model and the distribution risk maps.

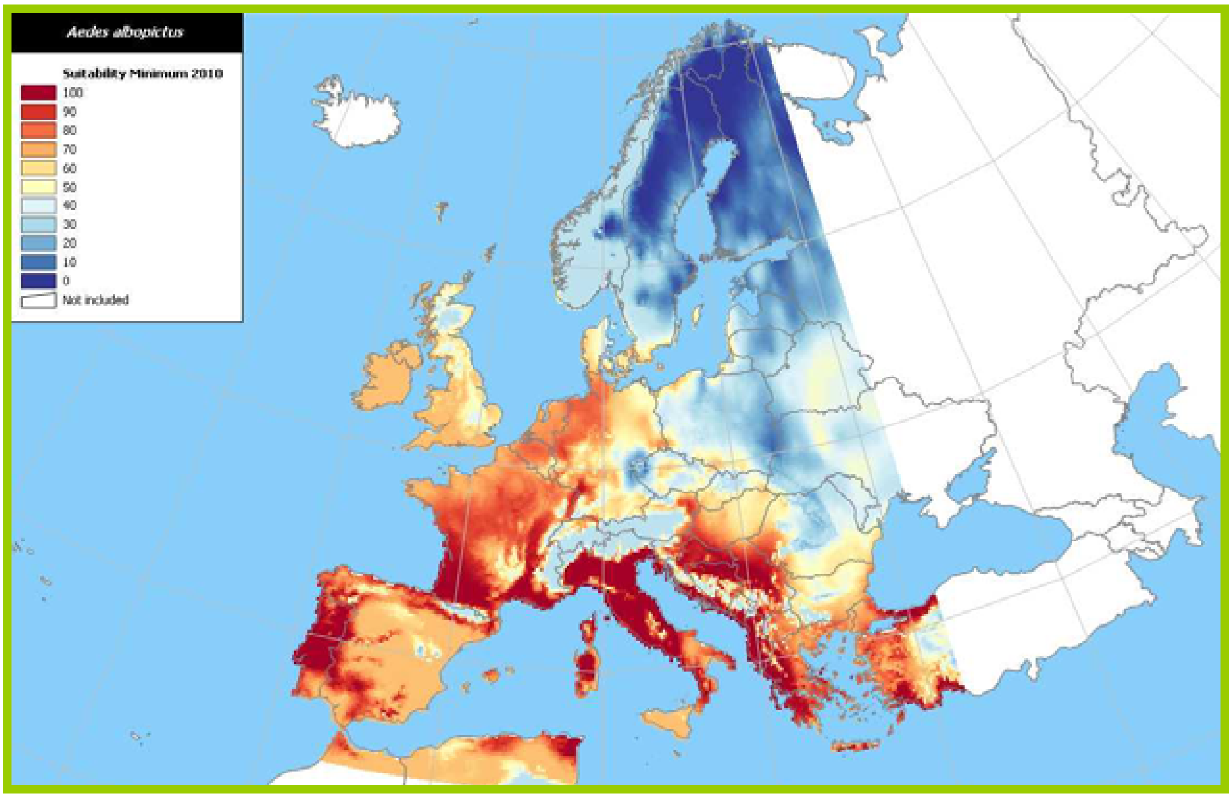
Map 7 a–d. Prospective impact of climate change on *Aedes albopictus* distribution in Europe

The following pages present a series of suitability maps for the presence of *Aedes albopictus* based on multi-criteria decision analysis; the temperature and rainfall data used for these maps were predicted by various IPCC climate scenarios. Figures A and B indicate suitability for two minimal-change scenarios: short-term (2010) or long-term (2030). Figures C and D indicate suitability for two maximum-change scenarios: short-term (2010) or long-term (2030).

Colours indicate the suitability levels, from dark blue (less suitable areas) to dark red (most suitable areas).

Minimal impact: short-term change scenario

Figure 7a (i). Prospective impact of climate change on *Aedes albopictus* distribution in Europe: minimal impact, short-term change scenario



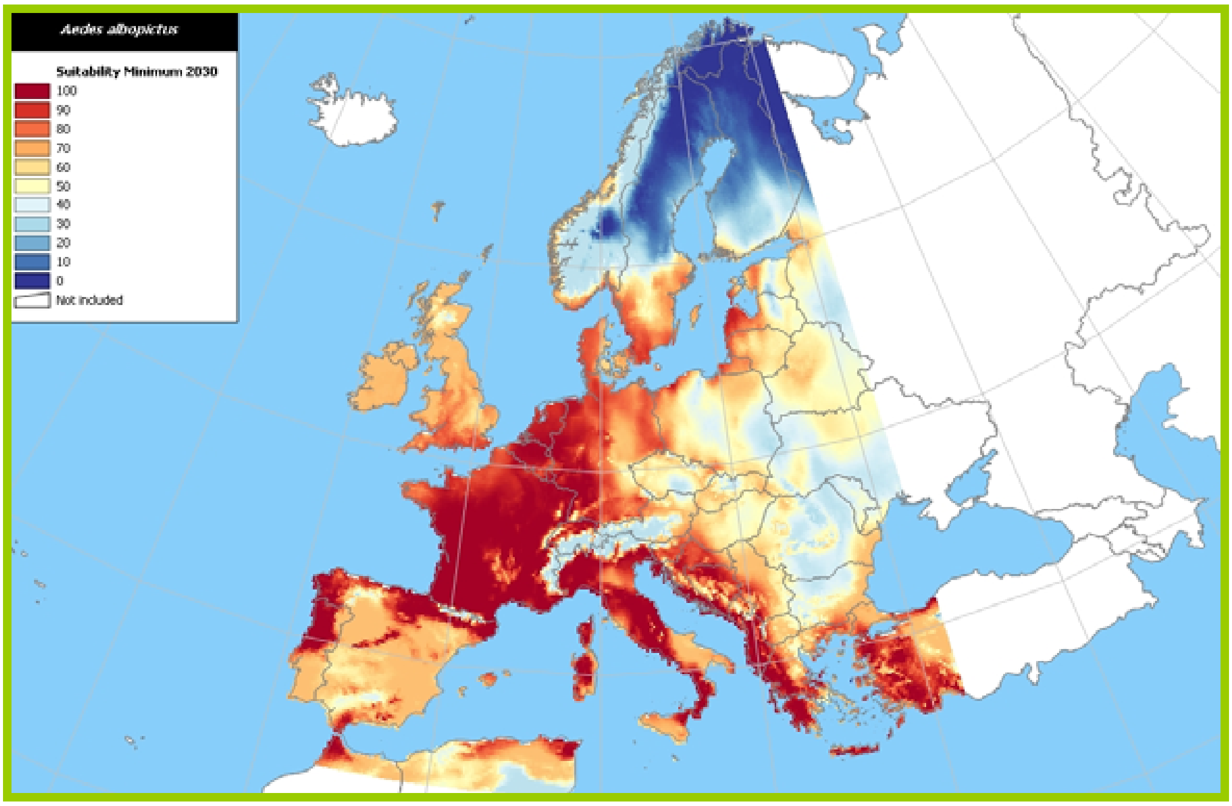
Compared to the current situation, the minimal impact short-term projections for 2010 show changes in two areas: in central Europe (up to the southernmost parts of Sweden) and in the Balkan. These areas are becoming significantly more suitable.

Minimal impact: short-term change scenario, observed differences

Figure 7a (ii). Observed differences with normal situation (Figure 5)

Minimal impact: long-term change scenario

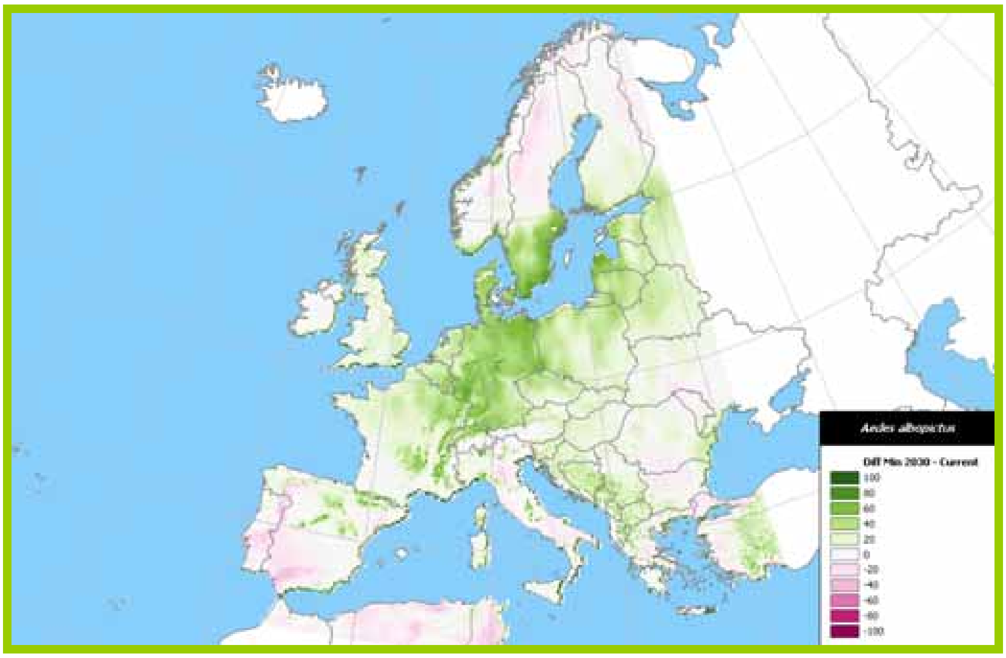
Figure 7b (i). Prospective impact of climate change on *Aedes albopictus* distribution in Europe: minimal impact, long-term change scenario



The minimal impact long-term projections for 2030 show a shift. While the central European zone (as described above) clearly extends in all directions and reaches as far as the Baltic states and even encompasses large parts of southern Sweden, the Balkan zone shrinks, with parts of Romania and Bulgaria now becoming unsuitable.

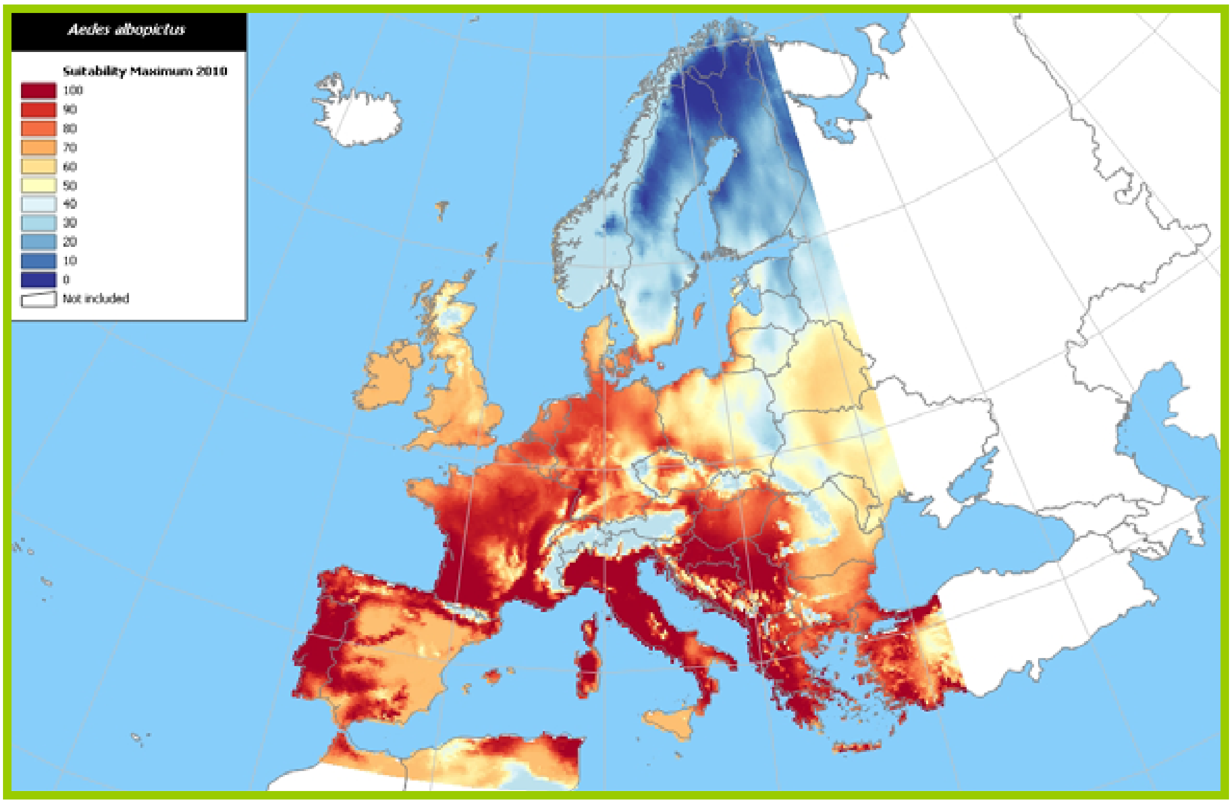
Minimal impact: long-term change scenario, observed differences

Figure 7b (ii). Observed differences with normal situation (Figure 5)



Maximum impact: short-term change scenario

Figure 7c (i). Prospective impact of climate change on *Aedes albopictus* distribution in Europe: maximum impact, short-term change scenario



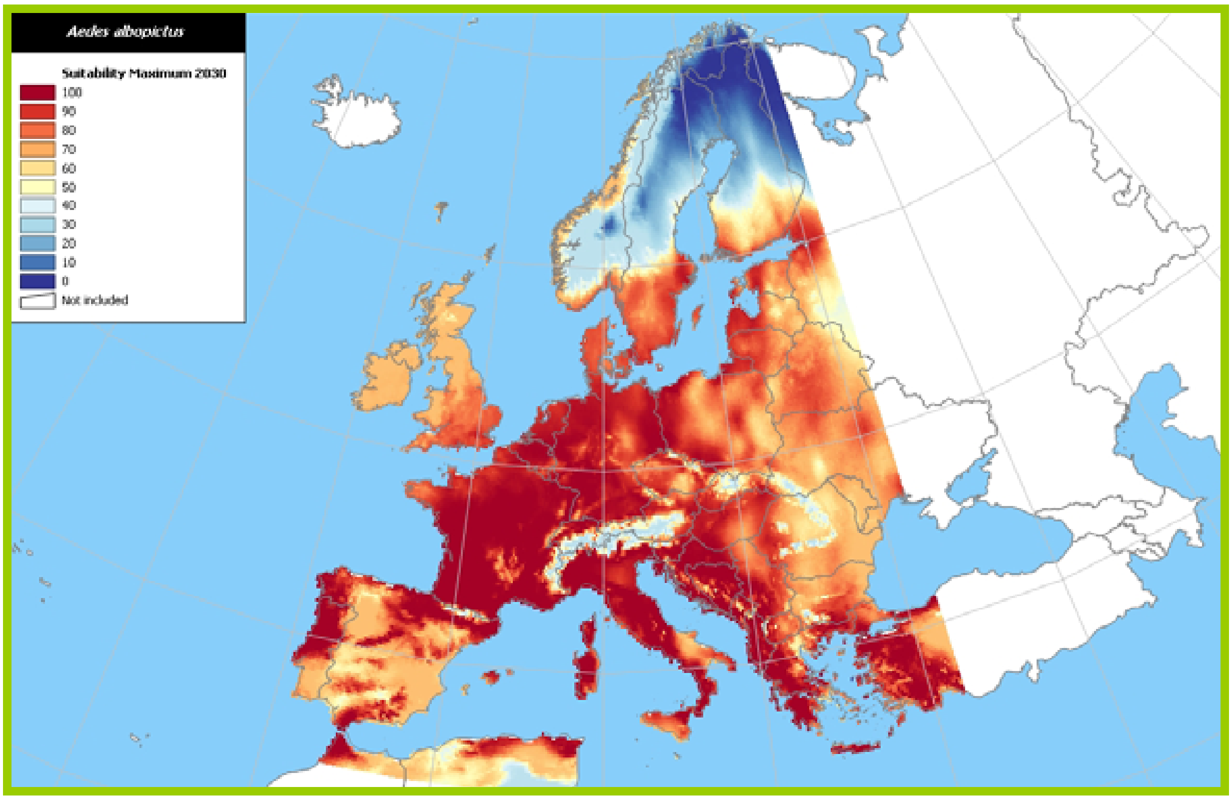
The short- and long-term projections are similar: both show a significant extension eastwards, suggesting that most of Europe would become suitable for *Aedes albopictus* should these scenarios become reality.

Maximum impact: short-term change scenario, observed differences

Figure 7c (ii). Observed differences with normal situation (Figure 5)

Maximum impact: long-term change scenario

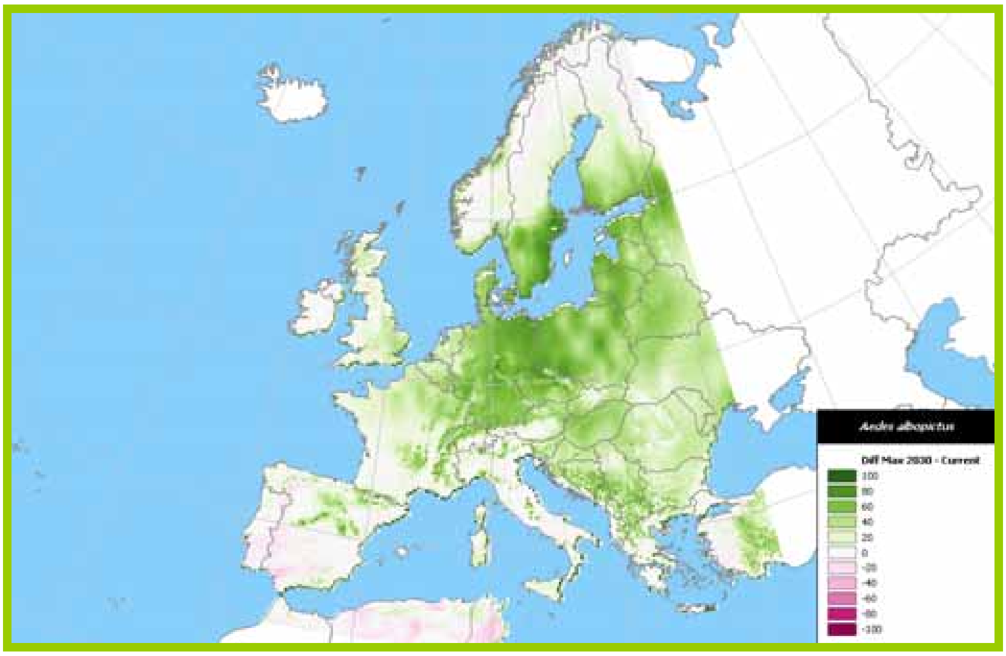
Figure 7d. **Prospective impact of climate change on *Aedes albopictus* distribution in Europe: maximum impact, long-term change scenario**



The short- and long-term projections are similar: both show a significant extension eastwards, suggesting that most of Europe would become suitable for *Aedes albopictus* should these scenarios become reality.

Maximum impact: long-term change scenario, observed differences

Figure 7d (ii). **Observed differences with normal situation (Figure 5)**



Annex 2: Table and list

Entomological data on surveillance and control of *Aedes albopictus* (table)

Table 6. **Entomological data on surveillance and control of *Aedes albopictus* and other mosquitoes, and source of information, for European states.**

Information quality	Country	Mosquito study or surveillance during the last five years				Mosquito control programme during the last five years				Surveillance for *Ae. albopictus* during the last five years				Surveillance since	*Ae. albopictus* control during the last five years				Type of control programme		Organisation of control programme		presence	first report	Type of occurrence		Nuisance		source of information	Contributors
		national	regional	regular	occasional	national	regional	regular	occasional	national	regional	active	passive		national	regional	regular	occasional	larval	adult	public	private			homogenous	isolated foci	complaints	no complaints		
C	Albania	-	-	-	-	-	-	-	-	•	-	•	-	Oc	-	•	•	-	-	•	-	•	yes	79	•	-	•	-	PB/PC	E. Velo, S. Bino
C	Andorra	•	-	•	-	-	-	-	-	•	-	•	-	Oc									no						PC	M. Domènech Ferrés, C. Aranda
I	Austria	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	W. Lechtaler
N	Belarus																						ni							
C	Belgium	•	-	•	-	-	-	-	-	•	-	•	-	07	-	-	-	-	-	-	-	-	no[1]	00[1]	-	-	-	•	PB/PC	W. Van Bortel
I	Bosnia and Herze-govina	-	•	•	-	-	•	•	-	-	-	-	-	-	-	-	-	-	-	-	-	-	yes	05	-	•	-	-	PC	D. Petrić
I	Bulgaria	-	•	-	•	-	-	-	-	-	-	-	-	-									n/nd						PC	M. Andreasen, Y. Kutsarov
C	Croatia	-	•	•	-	-	•	•	-	-	•	•	-	00	-	•	•	-	•	•	•	-	yes	04	•	-	•	-	PB/PC	E. Merdic
I	Cyprus	•	-	•	-	-	•	•	-	-	-	-	-	-									no						PC	M. Vasquez
C	Czech Republic	-	•	•	-	-	•	•	-	-	•	•	-	Oc									no						PC	F. Rettich
C	Denmark	-	•	•	-	-	-	-	-	-	-	-	-	-									no						PC	B. Nielsen
I	Estonia	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	K. Kutsar
I	Faroe Islands (DK)	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	B. Nielsen
I	Finland	-	•	-	•	-	-	-	-	-	-	-	-	-									n/nd						PC	L. Huldén
C	France	-	•	•	-	-	•	•	-	•	-	•	-	99	•	-	•	-	•	•	•	-	yes	99	•	-	•	-	PB/PC	C. Jeannin
C	Germany	-	•	•	-	-	•	•	-	-	•	•	-	05	-	-	-	-	-	-	-	-	yes	07	-	•	-	•	PC	B. Pluskota
I	Gibraltar (UK)	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	J. Medlock
C	Greece	-	•	•	-	-	•	•	-	-	•	•	-	06	-	•	-	•	-	•	•	-	yes	03	•	-	•	-	PB/PC	A. Samanidou, N. Voutsina, S. Gewehr
C	Guernsey (UK)	•	-	•	-	-	-	-	-	•	-	-	•	06									no						PC	J. Medlock
I	Hungary	-	-	-	-	-	-	-	-	-	-	-	-	-									nd[2]						PC	L. Papp
N	Iceland																						ni							
C	Ireland	-	•	-	•	-	-	-	-	-	-	-	-	-									n/nd						PC	K. McCarthy
C	Isle of Man (UK)	•	-	•	-	-	-	-	-	•	-	-	•	06									no						PC	J. Medlock
I	Italy	-	•	•	-	-	•	•	-	-	•	•	-	00	-	•	•	-	•	•	•	•	yes	90	•	-	•	-	PB/PC	R. Romi, P. Angelini, R. Bellini, A. Talbalaghi, C. Venturelli, R. Zamburlini, and colleagues.*

Information quality	Country	Mosquito study or surveillance during the last five years				Mosquito control programme during the last five years				Surveillance for *Ae. albopictus* during the last five years				Surveillance since	*Ae. albopictus* control during the last five years				Type of control programme		Organisation of control programme		presence	first report	Type of occurrence		Nuisance		source of information	Contributors
		national	regional	regular	occasional	national	regional	regular	occasional	national	regional	active	passive		national	regional	regular	occasional	larval	adult	public	private			homogenous	isolated foci	complaints	no complaints		
C	Jersey (UK)	•	-	•	-	-	-	-	-	•	-	-	•	06									no						PC	J. Medlock
I	Kosovo	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	D. Petrić
I	Latvia	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	V. Spungis
I	Liechten-stein	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	F. Schaffner
I	Lithuania	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	M. Žygutienė
I	Luxem-bourg	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	C. Meisch
N	Mace-donia																						ni							
N	Malta																						ni							
N	Moldova																						ni							
C	Monaco	•	-	•	-	•	-	•	-	-	-	-	-	-	-	-	-	-	-	-	-	-	yes	06	•	-	-	•	PC	F. Schaffner
C	Monte-negro	-	-	-	-	-	-	-	-	•	-	•	-	01	-	-	-	-	-	-	-	-	yes	01	•	-	•	-	PB/PC	D. Petrić
C	Nether-lands	-	•	-	•	-	-	-	-	•	-	•	-	05	-	•	-	•	-	•	-	•	yes	05	-	•	-	•	PB/PC	E.-J. Scholte
I	Norway	-	-	-	-	-	-	-	-	-	-	-	-	-									nd						PC	P. Ottessen
I	Poland	-	•	•	-	-	•	-	•	-	-	-	-	-									n/nd						PC	E. Wegner
I	Portugal	-	•	-	•	-	•	-	•	-	-	-	-	-									n/nd						PC	P. Almeida, M.J. Alves
I	Romania	-	•	-	•	-	-	-	-	-	-	-	-	-									n/nd						PC	F.L. Prioteasa
I	Russia	-	•	-	•	-	•	-	•	-	-	-	-	-									n/nd						PC	M. Sokolova
I	San Marino	-	-	-	-	-	-	-	-	-	-	-	-	-	?	?	?	?	?	?	?	?	yes	07	•	-	?	?	PC	P. Angelini
C	Serbia	-	•	•	-	-	•	•	-	•	-	-	•	05									no						PC	D. Petrić
C	Slovakia	-	•	-	•	-	-	-	-	-	-	-	-	-									no						PC	N. Jalili
C	Slovenia	-		-	-	-	-	-	-	-	-	-	-	Oc	-	-	-	-	-	-	-	-	yes	05	•	-	•	-	PC	E. Merdic, K. Kalan
C	Spain	-	•	•	-	-	•	•	-	-	•	•	-	03	-	•	•	-	•	•	•	-	yes	04	•	-	•	-	PB/PC	R. Eritja, C. Aranda, R. Escosa, J. Lucientes, E. Marquès, R. Melero, M.À. Miranda, D. Roiz, M. Rojo, J. Ruiz, S. Ruiz, A. Torrell
C	Sweden	-	•	•	-	-	•	•	-	-	-	-	-	-									no						PC	J. Lundström
I	Switzer-land	-	•	•	-	-	•	•	-	-	•	•	-	03	-	•	•	-	•	•	-	•	yes	03	-	•	•	-	PB/C	E. Flacio, F. Schaffner
C	Turkey	-	•	•	-	-	•	•	-	-	-	-	-	-									no						PC	B. Alten
C	United Kingdom	•	-	•	-	-	-	-	-	•	-	-	•	06									no						PC	J. Medlock
N	Ukraine																						ni							
C	Vatican City	-	-	-	-	-	-	-	-	-	-	-	-	-	?	?	?	?	?	?	?	?	yes	07	•	-	?	?	PC	C. Venturelli

Legend
C: complete; I: incomplete; N: nul
[greyed out field]: no information or not applicable
Oc: occasional
1: present in 2000 (absent in 2003 and 2007)
2: presence suspected in 2001
nd: no data
ni: no information
PB: publication; PC: personal communication
* see contributor list (Annex): 'Alphabetical list of TigerMaps contributors and their institutions'

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