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Mathematical modelling of the impact of climatic conditions in France on *Rhipicephalus sanguineus* tick activity and density since 1960

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Abstract. *Rhipicephalus sanguineus*, the brown dog tick, has a worldwide distribution in areas with a relatively warm climate, including mild winters. This tick plays an important role as vector for various animal and human pathogens, including bacteria and protozoa. Based on precise daily meteorological data from the past 40 years, combined with mathematical modelling designed to predict tick activity, two modelling approaches were developed. The first examined the evolution of the number of weeks with favourable biological conditions for ticks in four French cities located at various latitudes of the country: Nîmes in the south, Paris in the north, Lyon in the east and Nantes in the west. The second analysed the extension of the geographical surface area in km^2 where the biological conditions favour tick activity for at least 12 weeks per year. Both analyses revealed clear evidence of increased temperatures coupled with an augmented tick activity index in three of the four cities. However, the change was not significant in Nîmes, where the climate is Mediterranean and the tick is already endemic. For Paris, Lyon and Nantes, the activity index values have increased significantly, i.e. by 4.4%, 4.0% and 3.4%, respectively. The distribution of the activity index values is evolving strongly with significantly fewer values below 50% since the 1960s and a clear decrease of values between 20% and 50% during the latest decade. Between 1960 and 2000, the theoretical extension of the surface area where the climatic index is suitable for *R. sanguineus* has increased by 66%. Even though several other important factors, such as changes in biotopes or human activity, are not included in this study, the resulting patterns and trends are noticeable. Our models constitute the first demonstration of the impact of climate change on the activity and distribution of ticks and confirm the observed northward migration trend for this Mediterranean domestic tick.

Keywords: *Rhipicephalus sanguineus*, mathematical modelling, climate change, epidemiology, France.

Introduction

The past few years have seen the emergence of new diseases, or re-emergence of existing ones, usually with changes in their epidemiology (i.e. geographical distribution, prevalence and pathogenicity) (Beugnet and Marié, 2009). The frequency of some tick-borne diseases of pets is increasing in Europe, for example canine babesiosis, granulocytic anaplasmosis, canine monocytic ehrlichiosis and thrombocytic anaplasmosis (Beugnet and Marié, 2009; Gray et al., 2009). The southern limit of canine monocytic ehrlichiosis and canine thrombocytic ehrlichiosis has shifted northwards with autochthonous cases seen in the northern part of France (Beugnet, 2010; Doudier et al., 2010). Both the distribution and the density of the three main European tick species, *Rhipicephalus sanguineus*, *Dermacentor reticulatus* and *Ixodes ricinus* are changing (Gray et al., 2009). The density of the forest tick *I. ricinus* appears to have increased, and hence the risk of transmission of *Borrelia*, *Anaplasma*, and several Ricketssiae has increased (Lindgren et al., 2000; Gern et al., 2008). While the distribution of *D. reticulatus* seems to have been extended throughout all of continental Europe (Dautel et al., 2006; Bullova et al., 2009), a clear expansion to the north has recently been reported for the Mediterranean tick *R. sanguineus*, also called the brown dog tick or the kennel tick (Dantas-Torres, 2010). The underlying conditions behind such changes are primarily human factors such as travel with pets and changing social/leisure activities (Harrus and Baneth, 2005) but involve also:

(i) landscape changes such as the creation of recreational parks facilitating the establishment of tick populations close to human habitation, which leads to increased potential for disease exposure;
(ii) measures to protect wild fauna, combined with

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land rehabilitation and management practices, particularly in forestry, which contribute to proliferation of potential tick hosts, i.e. deer, wild boar, foxes and rodents; and
(iii) climate change, which has a direct impact on arthropod vectors (host density, geographical distribution and vector capacity), especially allowing southern species to move northward (Randolph, 2010).

The reduction of the winter period constitutes a proven climate change, which should have an impact (Lindgren et al., 2000). For example, a mild winter with fewer days with temperatures below 0 °C would allow more generations of *Ixodes* and *Dermacentor*, whereas it would allow *R. sanguineus* to survive and establish at northern latitudes (Marhenholz, 2008; Gray et al., 2009). This tick species, which shows a strong preference for feeding on dogs, is found almost worldwide and its feeding habits provide the potential for the development of large populations (Dantas-Torres, 2010). The *R. sanguineus* ticks are often observed crawling around baseboards, up the walls or other vertical surfaces of infested homes seeking protected areas, such as cracks, crevices, spaces between walls or wallpaper, where they moult or lay eggs. It is a known vector of canine ehrlichiosis (*Ehrlichia canis*), canine babesiosis (*Babesia canis vogeli* or *B. gibsoni*), *Anaplasma platys* and may be associated with the transmission of *Bartonella vinsonii* in dogs. *R. sanguineus* is also the vector of the filarids *Acanthocheilonema reconditum*, *A. dracunculoides* and *Cercopithifilaria grassii* in dogs and has been implicated as vector of human pathogens in some areas of the world. For example, in Europe, Asia and Africa, it can serve as the vector of *Rickettsia conorii*, the causative agent of Mediterranean spotted fever (Parola et al., 2005; Nicholson et al., 2010).

Since many studies reported modified geographical distribution of ticks due to climate change, we were motivated to assess whether variations in temperature and humidity conditions have led to changes in tick abundance in Europe. We constructed a meteorological model for tick activity, whose accuracy has been checked by field tick sampling in Europe (Beugnet et al., 2009; Beugnet, 2010). Although this model does not predict the tick presence based on biotope (biotope suitability models) even if it includes adjustment coefficients, it predicts "climatic suitability", i.e. the positive or negative impact of local temperature and humidity and their variation throughout the year (Koch et al., 2007). In order to avoid any bias due to fauna or biotope modifications, *R. sanguineus*, a domestic tick with tropism for dogs at every stage of its lifecycle (larvae, nymphs and adults), was chosen.

Materials and methods

This study was designed to investigate the variations of the activity index of *Rhipicephalus* ticks throughout Europe and North Africa during the period 1960-2000. Two distinct analytical paths were followed: the first was a duration-type analysis constituting the study of the number of weeks (consecutive or not) during which the weekly activity index given by the meteorological model in one designated area remains above 30%, 40% or 50%. The figures give the probability of the number of ticks out of 100 specimens capable to search and infest a host and, for the bloated stages on the ground, to moult or to lay eggs (the biological activity index is calculated as shown below). Our hypothesis was that a biological index above 40% during a period of several weeks (>12) allows a tick population to install itself and become endemic. The selected places were all located in France, i.e. in Paris, Lyon, Nantes and Nîmes. This choice was based on the hypothesis of the northward extension mentioned above. Nîmes is located in the South, with a clear Mediterranean climate and *R. sanguineus* is the dominant dog tick there. Nîmes served as the presumed "negative control", as we did not expect any modification in an already endemic area. Lyon, located 217 km north of Nîmes and characterised by a continental climate was chosen since it is non-endemic with regard to *Rhipicephalus*. Nantes, located on the west coast and with an Atlantic temperate climate which, according to several models (Estrada-Peña, 2008; Gray et al., 2009), could permit *Rhipicephalus* to become established. Paris, located in northern France 450 km from Lyon and 660 km from Nîmes, was chosen since *Rhipicephalus* should not be able to establish itself there due to prevailing climate factors in this area. As we focused on the meteorological changes, the biotope variations were not included in the comparison of the city characteristics.

The second path was an extension-type analysis constituting the study of the change in geographical extent of areas where the activity index for *Rhipicephalus* remains above 30%, 40% or 50% during a period of at least 12 weeks in a year.

Calculation of the biological activity index

The "FleaTickRisk" model is based on accurate meteorological data in order to forecast and to monitor the activity and density of some arthropods throughout Europe (Beugnet et al., 2009). It uses outputs of the Weather Research and Forecasting (WRF) (http://www.wrf-model.org/index.php) meteorological model and integrated biological parameters (Michalakes et al., 2001; Skamarock, 2008) and provides values of weather parameters, among which temperature and humidity are measured four times a day (at 0:00, 6:00, 12:00 and 18:00 hours). Its geographical resolution is 27 x 27 km over Europe (an area roughly situated between the longitudes 10.5° W and 30° E and the latitudes 37.75° N and 62° N). The model also provides weekly forecasts. Past data are compared and revalidated using current meteorological data generated by ground stations and weather satellites (Wimberley et al., 2008). The WRF model also includes geographical information, such as elevation and biotope maps, from United States Geophysical Survey (USGS) (http://www.usgs.gov), taking into account specific climatic conditions due to valleys, altitudes, lakes and winds.

The tick activity index is defined by its ability to infest hosts, take blood meals and reproduce, and these parameters are influenced by the prevailing weather conditions. Table 1 shows the biological activity parameters of *R. sanguineus* transformed into a matrix according to Jacobs et al. (2004). A percentage of activity is given for each temperature/humidity couple and we considered that an activity index above 40% means highly favourable biological conditions for the tick. The matrix is calculated using existing data collected under optimal temperature and humidity conditions, as well as the timing of the life cycle. The mathematical model integrating both the WRF model (meteorological data plus geographical data) and the biological matrix provides two indexes: an activity index (ranging from 0 to 100), calculated for the previous week and predictive for the coming week, and a cumulative index (ranging from 0 to 1,000), which takes into account the past 12 weeks. The indexes are calculated twice a day for each geographical point all over Europe and corrected according to three types of defined biotopes: urban/sub-urban areas, rural areas, and wilderness/forests. The indexes are gathered within intervals and are presented as colour maps, which group index isoclines.

In the present study, the temperature/humidity data came from models other than the WRF one, but the mode of calculation of the index remain the same: the activity index (expressed as a percentage) is a function of daily temperature and daily humidity taken at 12:00 and 18:00 hours. The percentage of the weekly tick activity index is the average of the daily activity index. The so-called "activity index" could therefore be named "tick climate fitness (TCF) index".

Climatic data used for the modelling

The WRF outputs used for FleaTickRisk could not be used for this study, since the first available data correspond only to dates after 2008. Therefore, the climatic data used to calculate the biological activity index of the tick came from the European Research and Development project called ENSEMBLES (http://ensembles-eu.metoffice.com) discussed by Hewitt and Griggs (2004).

The research topic no. 3 (RT3) consisted of: (i) the construction of a network of daily meteorological data covering whole Europe with a resolution of 0.25° between 1950 and 2006 (Haylock et al., 2008); and (ii) the integration of several regional climate models (RCMs) forced by the European Centre for Medium-range Weather Forecasts (http://www.ecmwf.int/) analyses (ERA-40) from 1960 to 2000.

Table 1. The biological activity matrix for *Rhipicephalus*.

	Temperature							
	<10 °C	10-15 °C	15-20 °C	20-24 °C	24-30 °C	30-35 °C	35-40 °C	>40 °C
Humidity								
<20%	0	0	0	0	0	0	0	0
20-40%	0	10	10	30	30	20	0	0
40-50%	0	10	30	60	80	30	0	0
50-60%	0	10	30	100	100	40	10	0
60-70%	0	10	30	100	100	60	10	0
70-80%	0	10	30	100	100	60	20	0
80-90%	0	10	30	100	100	80	30	0
>90%	0	10	30	100	100	80	50	0

The activity varies with humidity and temperature according to the biological adaptation of the tick in question. The European peak of activity for *R. sanguineus* falls in an area that consists of the summer months in the Mediterranean part of Europe.

The 40-year, high-frequency (4-daily) temperature and humidity data at 2 m above ground were kindly provided by Environment Canada (http://www.ec.gc.ca/) as an output of their own regional model (Zadra et al., 2008). The study area was divided into a regular grid (longitude-latitude) using a scale of 0.25° including 470 longitude points and 213 latitude points. In order to avoid any bias due to the regional model, a correction was applied to the model on temperature outputs using the daily grid observations from ENSEMBLES. The methodology is as follows:

$$T^{unbiased}_{RCM} = \overline{T_{OBS}} + T'_{RCM} \quad \text{with} \quad T'_{RCM} = T_{RCM} - \overline{T_{RCM}}$$

Where T = the daily average, RCM = regional climate model data, and OBS = the observed data from the ENSEMBLES dataset (Zadra et al., 2008). Figure 1 shows that the correction is significant because the unbiased curve completely superimposed the observed data. Note that data from the corrected model allows the calculation of all the daily temperature/humidity values even when real observations are missing.

Results and discussion

Activity index evolution in French cities between 1960 and 2000

The average tick climate fitness (TCF) index of *R. sanguineus* throughout the 40-year period is shown in Figure 2. Clearly, the TCF index is above 35% at the location of Nîmes, whereas the three other cities are in areas where the daily average of the index is low (between 15% and 25%).

Nîmes: the evolution of the monthly TCF index for Nîmes during the study period is shown in Figure 3a. The linear regression shows a limited positive trend, with a difference in index values of 2.9% between 1960 and 2000. However, when a Loess filter (Saporta, 1990) is applied to the evolution curve, it is apparent that the trend is not regular, with negative trends at the beginning of 1970 and 1980 and a peak during the summer of 1977. The probability density functions of the *Rhipicephalus* TCF index have been estimated and are shown in Figure 3b for the last four decades of the 20th century. The distributions of these four decades were not found to be significantly different (Cramér-von Mises distance with 5% significance test) (Darling, 1957). Even if not significant, the 1990-2000 decade shows fewer values below the index of 10%.

Lyon: the linear regression during the 40 years shows a positive trend with a difference in TCF index of 4% between 1960 and 2000 (Fig. 4a). This trend is not uniform and the Loess filter indicates negative trends in the early 1960s and 1970s, as well as in the mid-1980s and 1990s. Activity peaks are seen in 1970, 1980 and at the end of 1990. The comparison of the four decades is shown in the figure 4b. A Cramér-von Mises test was carried out in order to compare the distribution with a threshold of significance of 0.05. Except the decade of 1980, the 1970s and 1990s are significantly different from the 1960s, which was used as the reference value. The distributions of the three last decades are broader than in the 1960s, which

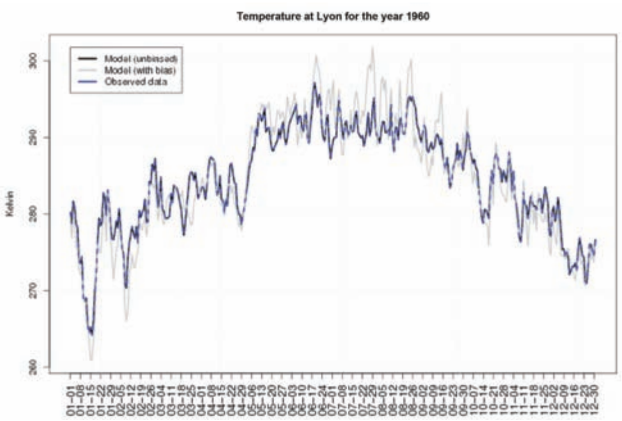

Fig. 1. Regular sampling of the daily temperature (Kelvin scale) in Lyon in 1960. The figure illustrates the bias correction (black) applied to the regional model. This curve is almost completely covered by the curve representing the real data (blue). The display illustrates that the correction of the model fits extremely well with the observed data.

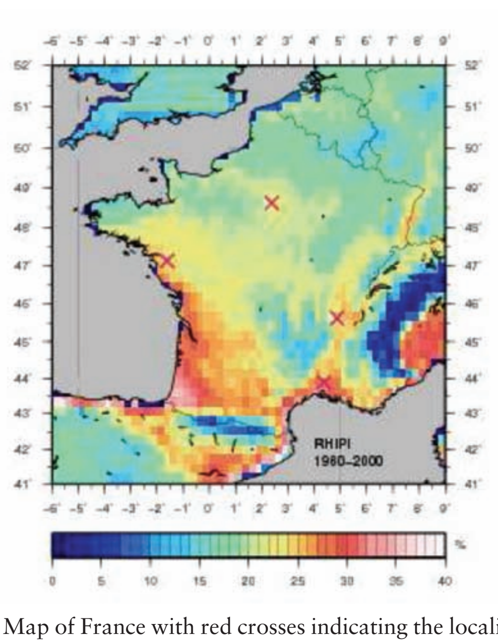

Fig. 2. Map of France with red crosses indicating the localisation of the four study cities, which are superimposed on a map with the average activity index for *Rhipicephalus* for 1960-2000 (sliding-scale with blue colours for low and red for high activity). Only Nîmes is associated with an area, where the 40-year daily average of the TCF index appears to be above 35%.

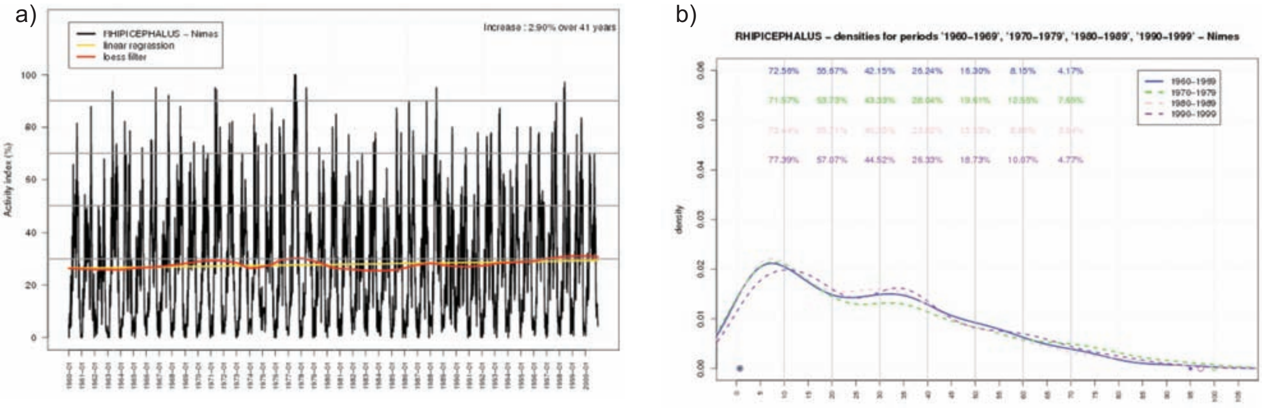

Fig. 3. The TCF index for *R. sanguineus* in Nîmes (France) during the period 1960-2000. a) Monthly evolution of the TCF index during the period 1960-2000 for the city of Nîmes. The thresholds are indicated by the horizontal grey lines. The yellow line is the linear regression of the data. The red curve represents a second-order Loess filter with a 10-year window. b) Density probability of the activity index for the city of Nîmes during the four decades of 1960-1969, 1970-1979, 1980-1989 and 1990-1999. The activity thresholds are displayed as vertical grey bars. The percentages in colour on the grey lines correspond to the proportion of activity index values above the threshold for each decade. The dots on the curves are showing the minima and maxima for each distribution.

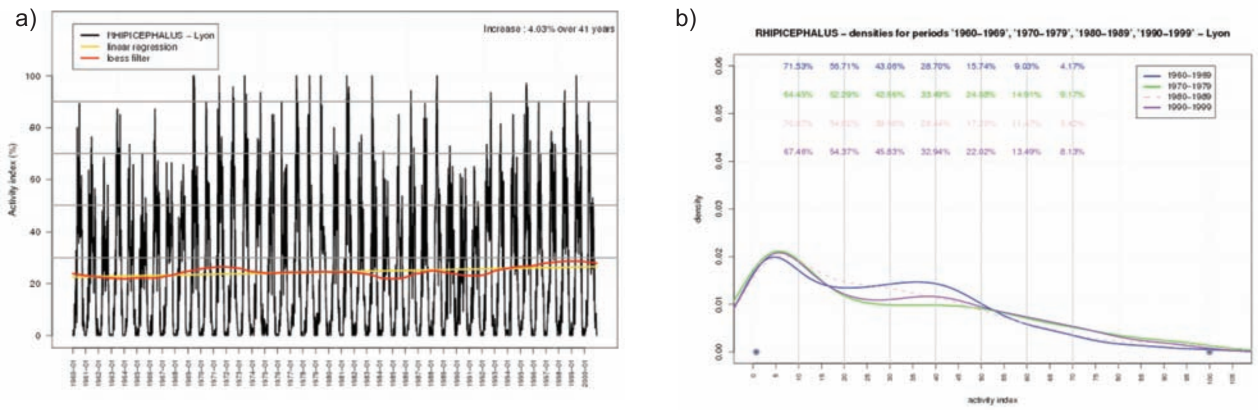

Fig. 4. Study of the TCF index of *R. sanguineus* in Lyon (France) during the 1960-2000 period. a) Monthly evolution of the activity index during the period 1960-2000 for the city of Lyon. The thresholds are indicated by the horizontal grey lines. The yellow line is the linear regression of the data. The red curve represents a second-order Loess filter with a 10-year window. b) Density probability of the activity index for the city of Lyon during the four 10-year periods of 1960-1969, 1970-1979, 1980-1989 and 1990-1999. The activity thresholds are displayed as vertical grey lines. The percentages in colour on the grey lines correspond to the proportion of activity index values above the threshold for each decade. The dots on the curves are showing the minima and maxima for each distribution.

means a more suitable climate for the brown dog tick. The past 30 years have more index values above 50% than in the 1960s. For example, during the 1970s, 1980s and 1990s, there were 24.1%, 17.2% and 22.0%, respectively, of the value above index 50, compared to 15.7% during the first decade. Similarly, there are fewer values of indexes between 20 and 40 than in the 1960s. It clearly indicates a positive influence of the climate on the installation of the brown dog tick during the past 40 years in the Lyon area.

Nantes: Figure 5a shows a positive linear trend for Nantes, with a difference of 3.4% between the values in 1960 and in 2000. This trend is not uniform but less irregular than for the other cities, which could be related to the oceanic climate being more stable throughout the year. Activity peaks can be noted in 1977 and 1988. The comparison of the decades is shown in Figure 5b. The 1970s is the only decade to be significantly different from the 1960s (Table 2). Like Lyon, the evolution is towards more values above the threshold of 50% or 70% and less values below the index threshold of 40%. It indicates that *Rhipicephalus* climate suitability has improved significantly in this area during the past 40 years.

Paris: as shown in Figure 6a, the linear regression indicates an increase of the value of 4.4 between 1960 and 2000. This positive trend is not regular. The Loess filter indicates local negative regression in the first half

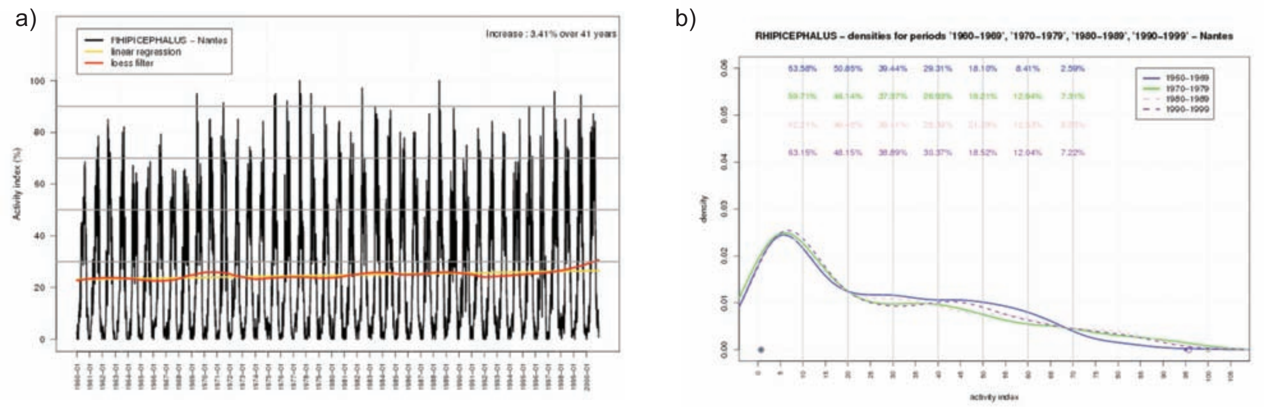

Fig. 5. Study of the tick climate fitness index of *R. sanguineus* in Nantes (France) during the period 1960-2000. a) Monthly evolution of the activity index during the period 1960-2000 for the city of Nantes. The thresholds are indicated by the horizontal grey lines. The yellow line is the linear regression of the data. The red curve represents a second-order Loess filter with a 10-year window. b) Density probability of the activity index for the city of Nantes during the four 10-year periods of 1960-1969, 1970-1979, 1980-1989 and 1990-1999. The activity thresholds are displayed as vertical grey lines. The percentages in colour on the grey lines correspond to the proportion of activity index values above the threshold for each decade. The dots on the curves are showing the minima and maxima for each distribution.

Table 2. Statistics from the test of Cramér Von Mises for the four cities and critical values ($\alpha = 0.05$)

	Lyon	Paris	Nantes	Nîmes
Period 2 *vs.* 1	0,898*	1,009*	0,609*	0,204
Period 3 *vs.* 1	0,213	0,555*	0,280	0,117
Period 4 *vs.* 1	0,472*	0,698*	0,189	0,309
Threshold values at α = 0,05	0,461	0,461	0,461	0,461

* Significant difference at P <0.05

of the 1970s and 1980s and important peaks during the summers of 1969, 1977, 1983, 1998 and 2000. Figure 6b shows the distribution analysis of the TCF index values between the four decades. The three decades are significantly different from the 1960s. The distributions are broader after the 1960s and the number of TCF index values above 50% is significantly different from the first decade (17.2% in the 1970s, 15.6% in the 1980s and 17.6%, respectively, in the 1990s, compared to 12.3% in the 1960s). Similarly, TCF index values ranging between 20% and 50% are less numerous. These results are close to what was observed in Lyon. The study of the variation of the *Rhipicephalus* biological TCF index during a period of 40 years confirms our hypothesis, namely that the climate conditions are favourable and stable under Mediterranean conditions, as demonstrated by the situation in Nîmes. In the three other cities, there is a positive trend to more favourable conditions, which could allow this tick to be active and become endemic. This variation is seen over a relatively short period of 40 years. It could have been even greater by including the period 2000-2010 but the meteorological data are not yet available. From a biological point, it means that imported *Rhipicephalus* may find appropriate conditions to develop in a non-Mediterranean climate (Estrada-Peña, 2008; Randolph, 2010). Lyon and Paris seem better than Nantes for that purpose. The changes in temperature and humidity may be related to climate change but also to local modifications related to urbanization (Harrus and Baneth, 2005).

Spatial evolution of suitable conditions for the brown dog tick during the past 40 years

Another way to approach the changes on a larger scale is to try to evaluate the geographical extent of areas where the conditions are favourable for the tick biology and ecology over a time long enough to maintain or increase tick populations (Hewitt and Griggs, 2004; Wimberley et al., 2008). For that purpose, we

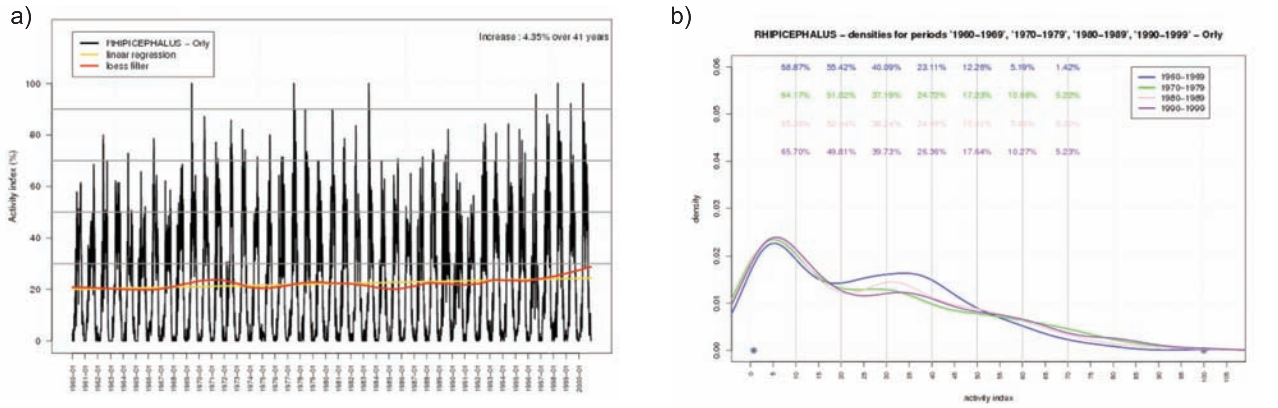

Fig. 6. Study of the tick climate fitness index of *R. sanguineus* in Paris (France) during the period 1960-2000. a) Monthly evolution of the activity index during the period 1960-2000 for the city of Paris. The thresholds are indicated by the horizontal grey lines. The yellow line is the linear regression of the data. The red curve represents a second-order Loess filter with a 10-year window. b) Density probability of the activity index for the city of Paris during the four 10-year periods of 1960-1969, 1970-1979, 1980-1989 and 1990-1999. The activity thresholds are displayed as vertical grey lines. The percentages in colour on the grey lines correspond to the proportion of activity index values above the threshold for each decade. The dots on the curves are showing the minima and maxima for each distribution.

considered a 12-week period during which the activity indexes were above a 30%, 40% or 50% threshold. Values of 20% or 60% are either too low or too high for a statistical analysis. A TCF index of 40% corresponds to favourable conditions for the development of the tick over a long term. The surface that was studied is the whole of Europe plus the border of North Africa (area between longitudes 10.5° W and 30° E and latitudes 37.75° N and 62° N).

Figure 7 represents the yearly evolution of the surface area when climatic conditions led to an activity index above 40% for at least 12 weeks a year. This criterion will be named “annual threshold”. The trend is shown as a linear regression in a grey line. The slope is noticeably positive and the area increased by 130,000 km^2 during the 40 years, which means a 66% expansion of suitable surface area. Nevertheless, the evolution was not regular and the application of a Loess filter (grey curve) allows the variations along the regression to be seen. The period from 1973 to 1988 showed a decrease in surface area following a peak in 1973. The study ends with a maximum in 1999. Setting the annual threshold at 30% or 50% leads to similar conclusions

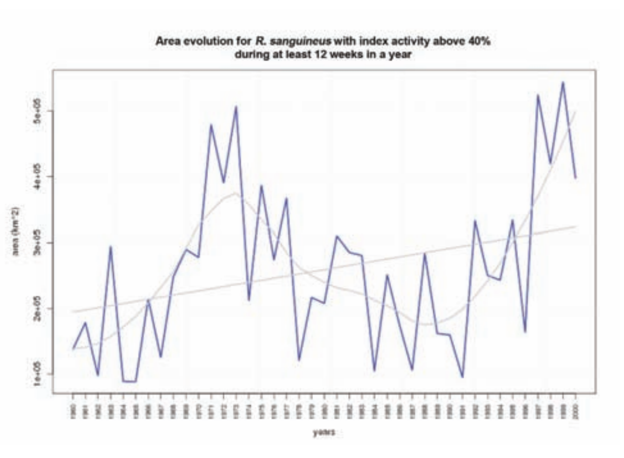

Fig. 7. Annual evolution in Europe and North Africa (north of Morroco and north-west of Algeria) of the surface area (in km^2) for which the biological activity index of *R. sanguineus* is above 40% during at least 12 weeks for the considered year.

Figure 8 represents the ratio of number of years with annual threshold of 40% for at least 12 weeks during the first and last decades. Over a period of 10 years, this leads to a value between 0 and 1. The southern part of Europe clearly appears more favourable. There is no significant variation for those areas which were already endemic for *R. sanguineus* in the first decade (south of Italy/Greece and north of Africa). It seems to be a negative trend for northern Italy between the first and the last decades but it is not significant. In contrast, what should be noted is that western and central Europe may have enough favourable conditions to let *Rhipicephalus* survive for 3 months. It confirms the analysis done for the French cities located west and north (Nantes and Lyon). Of course since this model makes assumptions based only on climatic conditions, many other criteria should be taken into account such as the existence of kennels, humidity on the grounds, density of dogs and winter conditions (Gray et al, 2009).

Conclusion

The study shows clear variations in the TCF index of *R. sanguineus* with respect to the climate change over the 1960-2000 period. Regarding the climatic

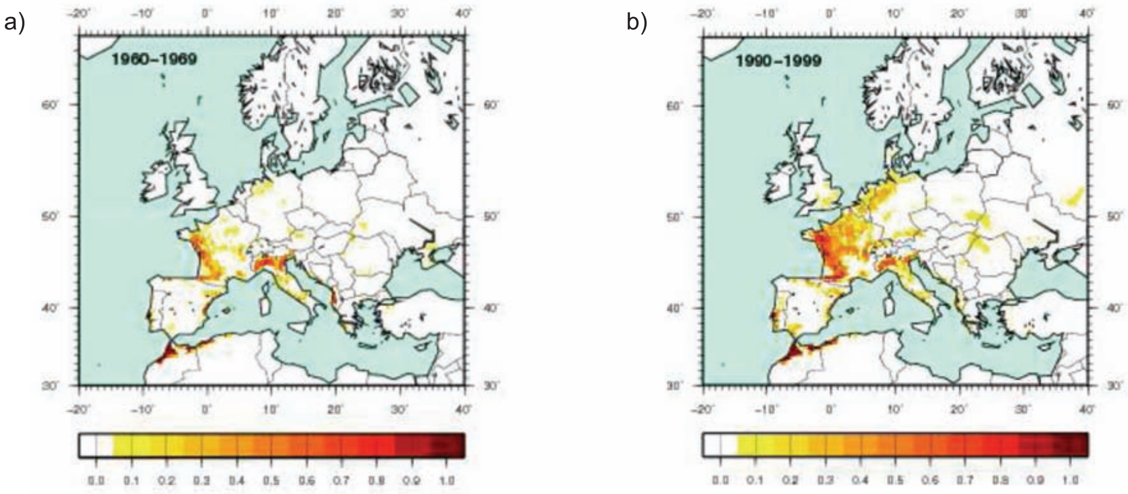

Fig. 8. Ratio of the number of years with an annual threshold of 40% for at least 12 weeks (between 0 and 1) for the period 1960-1969 (a) and 1990-1999 (b).

suitability in the four selected French cities, the activity index has increased significantly for three of them. Nîmes, where *Rhipicephalus* is already endemic, shows the smallest change due to its warm Mediterranean climate. For Paris, Lyon and Nantes, the activity index increased by 4.4%, 4.0% and 3.4%, respectively. As a matter of interest, the distribution of the index values has evolved significantly since the 1960s with fewer values below 50% and a clear decrease of TCF index values between 20% and 50% plus significantly more values above 50% for Lyon and Paris. This indicates an evolution towards more suitable biological conditions since the 1960s. The theoretical extension of the surface area, where the climatic index is suitable for *Rhipicephalus*, increased by 66% between 1960 and 2000 gaining 130,000 km² in the model. The northward shift is now well recognised by other European modelling or epidemiological surveys (Gray et al., 2009).

This study is the first demonstration of the climate impact on the activity and distribution of a domestic tick, carrying many pathogens of animal and human importance (e.g. *A. platys, B. canis vogelis, E. canis, Hepatozoon canis* and *R. conorii*) (Doudier et al., 2010). This impact is shown over a period of the past 40 years and highlights the importance of all networks working on arthropods and arthropod-borne diseases, especially the epidemiological changes for vectors including ticks and mosquitoes.

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