Impact of climate change on vector-borne disease in the UK

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Effect of climate change on vector-borne disease risk in the UK

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During the early part of the 21st century, an unprecedented change in the status of vector-borne disease in Europe has occurred. Invasive mosquitoes have become widely established across Europe, with subsequent transmission and outbreaks of dengue and chikungunya virus. Malaria has re-emerged in Greece, and West Nile virus has emerged throughout parts of eastern Europe. Tick-borne diseases, such as Lyme disease, continue to increase, or, in the case of tick-borne encephalitis and Crimean-Congo haemorrhagic fever viruses, have changed their geographical distribution. From a veterinary perspective, the emergence of Bluetongue and Schmallenberg viruses show that northern Europe is equally susceptible to transmission of vector-borne disease. These changes are in part due to increased globalisation, with intercontinental air travel and global shipping transport creating new opportunities for invasive vectors and pathogens. However, changes in vector distributions are being driven by climatic changes and changes in land use, infrastructure, and the environment. In this Review, we summarise the risks posed by vector-borne diseases in the present and the future from a UK perspective, and assess the likely effects of climate change and, where appropriate, climate-change adaptation strategies on vector-borne disease risk in the UK. Lessons from the outbreaks of West Nile virus in North America and chikungunya in the Caribbean emphasise the need to assess future vector-borne disease risks and prepare contingencies for future outbreaks. Ensuring that adaptation strategies for climate change do not inadvertently exacerbate risks should be a primary focus for decision makers.

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Introduction

The Intergovernmental Panel on Climate Change report[1] emphasises several infectious disease issues that might be exacerbated by climate change. The focus of the report was largely the changes in infectious disease (particularly vector-borne disease) in tropical countries, with a section on some of these infectious disease risks in the chapter about Europe.[1] It is a generally accepted within the report that direct effects of a 2°C, 4°C, and 6°C temperature rise on vector-borne disease risk cannot be predicted with any real confidence because of the complexities of the transmission cycles and the behavioural, ecological, and societal factors that cannot be captured directly within climate models. In this Review, we assess the potential effects of climate change on vector-borne disease, as they relate to UK public health, and we build upon the findings of the UK Health Protection Agency 2012 reports in *Health Effects of Climate Change in the UK*.[2] We do not address vector-borne diseases affecting animals only (ie, non-zoonotic). Vector-borne diseases are highly sensitive to changes in weather and climate. However, land-use changes and adaptation to climate change are also likely to affect the geographical distribution and incidence of vector-borne disease.

Vector-borne disease and climate change

Vector-borne diseases are transmitted by arthropod vectors (such as ticks and mosquitoes) and have increased substantially in their incidence and distribution in Europe in the past decade. Owing to the complexity of their transmission cycles, which often involves one or more arthropod vector species and several wild animal hosts, direct assessments of the effect of climate variables on their future spread or activity is not always possible.[2] That climate change will affect vector-borne disease is widely recognised, especially because arthropods are ectothermal and the extrinsic incubation of pathogens is widely temperature dependent. Very few assessments of the effects of 2°C, 4°C, or 6°C temperature increases have been made. The table summarises what evidence there is regarding the potential effect, where possible, of a 2°C temperature rise. The effects of temperature rises of 4°C and 6°C would tend in the same direction but are less easily quantified. As humans adapt to climate change, and as climatic and extreme weather factors affect habitats, there are a number of environmental changes that take place. These environmental changes, such as flood protection through provision of new wetlands or increased urban greenspace to minimise urban heat island effect, are designed to mitigate the effects of climate change. These environmental changes too can affect the risk of vector-borne disease, so a dynamic change in climate and weather cannot be considered in conjunction with a static view of land use.

Mosquitoes and mosquito-borne disease

Invasive mosquitoes: vectors of dengue fever, chikungunya, and yellow fever

Since 1990, five different species of *Aedes* mosquitoes have been introduced into Europe and subsequently become established, with three species becoming abundant and widespread.[14] Some of these tropical species have adapted to a temperate climate, and modelling predicts that current climate changes and predicted future climate change will permit the territorial expansion of these mosquito species across Europe,[5,15,16] including the UK, particularly southern England.[3] These invasive mosquitoes are imported through the global trade in used tyres and, to a lesser extent, ornamental plants,[14] although they are now also moving with vehicles along highway networks.[14] Some of the species are Asian in origin and have travelled to Europe via North America, where they were previously imported and established through imported tyre pathways. These invasive

	Current situation	Temperature-change assessment (+2°C)*	Confounders
Dengue virus or chikungunya virus	Main vectors are invasive mosquitoes, such as *Aedes albopictus*, expected to colonise UK in the future, and *Aedes aegypti*, less able to survive through UK winter; under a current climate scenario, *A albopictus* would be able to survive across large parts of England and Wales (up to 18 weeks elapsing between egg hatching in spring and autumn diapause of eggs, and up to 27–32 weeks between egg hatching and adult die off)[3]	Climate assessments suggest that UK climate is now suitable for *A albopictus*; climate change assessments for UK and Europe predict that southeast England will become more suitable for the establishment of *A albopictus*; an increased activity period of 1–2 weeks is expected for adult *A albopictus* in southern England by 2030–50, based on a 1°C annual temperature rise, and a 3–4 week extension of activity is expected for a 2°C annual temperature rise; an overall climate suitability increase of 15% by 2030–50 is expected, based on 1°C annual temperature change, and a suitability increase of 25–30% is expected, based on a 2°C annual temperature change); more than 80% agreement between Regional Climate Models;[4] climate change models for chikungunya predict suitable temperatures for 1 month of chikungunya virus transmission in London by 2041 and 1–3 months of virus transmission across most of southeast England by 2071–2100;[5,6] dengue risk will largely be linked to colonisation by *A aegypti*, which is not expected to become established up to 2100, and therefore the main dengue virus risk might come from *A albopictus*	Mosquitoes need to be imported by used tyres, or in vehicles from endemic areas; once established, they will colonise urban areas, and abundance will be proportionate to increasing temperatures and precipitation; however, the effect of peri-urban water storage would need to be considered
West Nile virus	UK has several endemic mosquito species that could potentially act as vectors; mainly *Culex* spp mosquitoes, including recently discovered species (*Culex modestus*); West Nile virus transmission is not considered climatically limited; absence of transmission might be due to low mosquito abundance for sustained transmission and, until recently, a restricted distribution of human biting *Culex* spp mosquitoes	Climate change would affect the biology and available habitats for mosquitoes, although other factors would need to be considered in a model; a 2°C increase in temperature would affect endemic mosquitoes by shortening their gonotrophic cycle and bloodmeal digestion, thus increasing abundance and shortening generation times, leading to increased cohorts of multivoltine species; there are no models to quantify this, however some data is available for some endemic *Aedes* species:[7,8] larval/pupal development lasts 38 days at 8°C and 18–20 days at 12°C; bloodmeal digestion lasts 30 days at 4°C, 14 days at 8°C, and 5 days at 20°C; embryonic development lasts 42 days at 4°C, 22 days at 12°C, and 8 days at 20°C	Climate change adaptation promotes wetland creation in coastal, rural, and urban locations; some of these will exacerbate *Culex* spp populations, human biting by a range of mosquito species, and increase in exposure to potential transmission cycles; birds would need to be infected to sustain transmission
Malaria	UK anophelines are considered competent vectors, although some species are now less anthropophilic; climate modelling has confirmed that transmission of *Plasmodium vivax* (and to a lesser degree *Plasmodium falciparum*) could already occur in the UK, although no cases are reported	Increasing temperatures will directly affect the parasite's development in the mosquito; one of five malaria effect models under the most extreme scenarios consistently predicts climate in southern England suitable for sustained *P falciparum* transmission (>1 month) by 2080, whereas another model predicts some suitability by 2030s; however, the other models predict no suitability, even by 2080; under medium–high scenario, a *P vivax* model[9] predicts that southern Great Britain will be climatically suitable for 2 months of the year by 2030 and for 4 months in parts of southeast England; by 2080, regions as far north as southern Scotland will be climatically suitable for 2 months, with 4 months suitability in southern Great Britain[10]	Human beings would have to sustain transmission as malaria is not zoonotic; antimalarials and public health care would minimise transmission to local cases
Lyme disease	Already endemic with more than 1000 confirmed cases each year; complex transmission cycle with positive and negative seasonal effects on tick activity from increasing temperature; tick seasonal activity is affected by changes in weather and climate; no long-term data exists on how climate has changed tick seasonality although these are being studied	Increasing temperatures will change the seasonal activity of ticks to earlier and later in the season, with reduced activity in the summer; a latitudinal and altitudinal spread is not expected to have a significant effect; evidence of altitudinal spread in central Europe of *Ixodes ricinus* from 700 m, between 1950 and 1980, to 1250 m by 2006; mean annual temperature had increased by 1·4°C between 1961 and 2005;[11,12] 400 km latitudinal shift in *I ricinus* distribution in past decades in Norway and Sweden, mainly linked to milder winters, longer vegetation period, and spread of deer[11]	The bacteria causing Lyme disease occurs in a range of wild mammals and wild birds, and models would therefore need to consider the effect of a changing climate on these host species, the seasonality and abundance of the tick, and the interactions between *Borrelia* genospecies; changing deer distribution or abundance and land-use changes (ie, urban greenspace) are likely to be more important factors in the changing human exposure to Lyme disease
Tick-borne encephalitis virus	Not endemic	Transmission of tick-borne encephalitis virus is highly reliant on co-feeding of different tick stages, which in itself is affected by weather and climate; current climate models do not predict an expansion of the range to the UK	See Lyme disease confounders; *I ricinus* is the likely vector
Crimean-Congo haemorrhagic fever virus	Not endemic because the vector is not endemic, although the vector is imported each year on migratory birds	Transmission is contingent on the vector becoming established; this needs higher temperatures for tick moulting, and there are no published models that make predictions for the UK	Most migratory birds in spring enter the UK from western Europe where Crimean-Congo haemorrhagic fever virus is not endemic; however, this could change
Mediterranean spotted fever	Not endemic because the tick vector was until recently rarely found in the UK	Since relaxation of tick controls on pets, the tick *Rhipicephalus sanguineus* is now imported regularly; it does not survive outdoors, but indoor survival is possible; although there are no models that include the UK, it is expected that a 2°C temperature rise could permit outdoor survival; a 2–3°C increase in mean temperature from April to September is expected to result in its establishment in regions of northern temperate Europe[13]	Dogs regularly import this tick into the UK; since it can survive indoors and feed on one host, it might become a vector regardless of ambient climate change

*Not all assessments are directly related to a 2°C average rise in annual temperature because some models relate to emission scenarios in 2041, 2071, and 2100.

Table: **Summary of evidence of the potential effect of a 2°C average rise in annual temperature**

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mosquitoes are all urban, exploiting the multitude of container habitats that proliferate near human dwellings. In addition to their biting nuisance, they are potential vectors of tropical diseases, such as dengue, chikungunya, and yellow fever.[14,17]

Aedes albopictus has now been reported in 25 different European countries (figures 1 and 2) and has become widely established in large parts of the Mediterranean Basin.[18] However, *A albopictus* has also been imported into the Netherlands, where they are found in commercial greenhouses and in water pooling in used tyres.[14] Concerns over their establishment in Europe have led to several EU-wide initiatives, led by the European Centre for Disease Control and Prevention, for enhanced distribution mapping (VBORNET/VECTORNET projects), climate change modelling, and development of surveillance and control guidelines.[19] Since 2007, *A albopictus* has been implicated in the transmission of chikungunya (>200 human cases in Italy) and dengue (isolated cases in France and Croatia), after these non-native mosquitoes acquired infection by blood-feeding from infected travellers.[17] In 2014, *A albopictus* was implicated in local transmission of dengue[20] and chikungunya[21] in southern France. *A albopictus* is abundant in most of Italy, along the Croatian coast, on the Côte d'Azur, and along the Spanish Mediterranean coast, where it is also a severe nuisance. This species continues to expand rapidly along road networks, particularly through France. *A albopictus* is expected to become established in northern France (including Paris) in the next few years, creating potential new routes for their importation into the UK. Imported human dengue cases in mosquito-endemic areas are treated as a matter of urgent control, particularly after localised transmission of dengue and chikungunya in southern France. In the event the mosquito should become established in the UK, the large numbers of imported dengue and chikungunya cases who travel to the UK would pose a source of infection to the established mosquitoes. However, onward transmission and the occurrence of autochthonous cases would depend on local climate conditions controlling the abundance of mosquitoes, and thus the rates of mosquito biting, and the virus.

Climate modelling by Public Health England and others[3,16] shows that the UK is climatically suitable for *A albopictus* and that the UK will become even more suitable with climate change. One of these studies[16] investigated climate change using three different mosquito-distribution models, all of which suggested that the present climate (based on data from 1990 to 2009) made large parts of the UK suitable for *A albopictus*, with greater suitability in the future. For two of the three models, there was agreement in eight of the ten regional climate models that southern England will be more suitable for *A albopictus* by 2030–50.[16] With a 1°C average rise in annual temperature, this climate change equates to an expected extension of 1–2 weeks in possible adult mosquito activity period for southern England by 2030–50. Whereas for a 2°C average rise in annual temperature, a 3–4 week extension of activity is expected. Overall climate suitability is expected to increase by 15% in 2030–50, on the basis of a 1°C average rise in annual temperature (25–30% increased suitability for a 2°C rise).

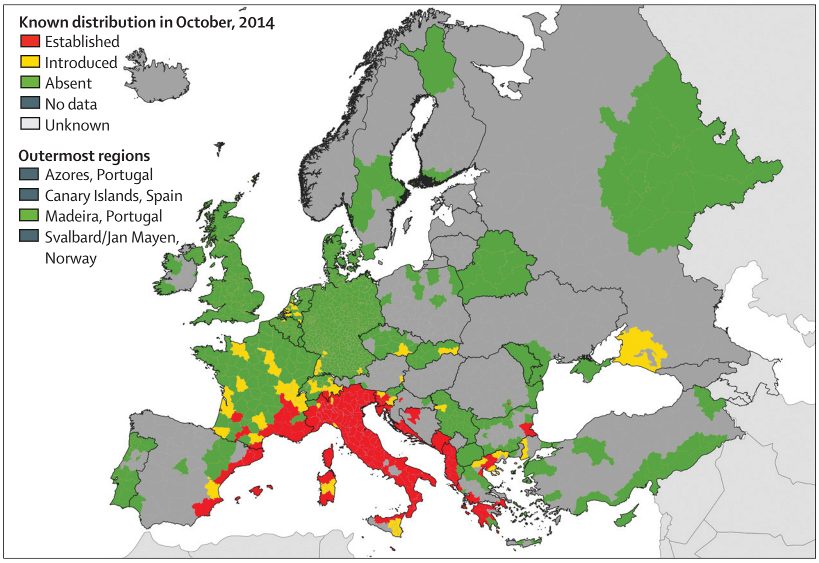

Figure 1: **Distribution of *Aedes albopictus* in Europe, October, 2014**
Source: ECDC-EFSA/VECTORNET.

Figure 2: **Blood-feeding female *Aedes albopictus* mosquito**

So far, Public Health England surveillance of mosquitoes at seaports, airports, and used tyre companies have not detected any non-native invasive mosquitoes.[22] However, the destination of imported tyres into the UK is not routinely recorded, and inspection at ports of containers or vehicles with imported used tyres is not done routinely. A better system to monitor imported used tyres is needed. In view of the northward transmotorway spread from southern Europe, Public Health England efforts have targeted service stations on motorways in southern England, particularly in view of the rapid northward spread of the mosquito in France.[23]

In the UK, 200–600 imported dengue cases and 15–300 imported chikungunya cases were reported each year between 2009 and 2014,[24] with cases of the latter having increased substantially in 2014, owing to the large-scale outbreak of chikungunya virus in the Caribbean, where there have been more than 1 million suspected cases.[25] An established invasive mosquito could enable autochthonous transmission of these viruses, as has occurred elsewhere in Europe,[17,20,21] and the risk will increase with rising annual temperatures. Pathogens in vectors undergo an extrinsic incubation period, which is the time taken between a vector acquiring an infectious agent and the point at which the vector is able to transmit that infectious agent to a susceptible host. This extrinsic incubation period is often temperature-dependent, and an understanding of this rate of development in local weather and in response to microclimates will enable a better prediction of the likelihood for local transmission. Models of chikungunya virus transmission from the EU suggest that with climate change, temperatures will be sufficient in London for at least 1 month of chikungunya virus transmission by 2041–70 and across most of southeast England for 1–3 months by 2071–2100.[5,6]

After many years of absence, *Aedes aegypti* re-established in Europe on Madeira in 2005, having previously been widespread in southern Europe.[14] In 2012, Madeira reported more than 2000 local dengue cases.[26] *A aegypti* is expected to spread to mainland Europe and will benefit from rises in temperatures.[17] So far, this species has not adapted to a temperate climate and is not expected to survive in a British climate, although adaptation can be rapid in mosquitoes. Results of modelling work of the suitability of Europe for dengue transmission by *A aegypti* showed that no parts of the UK would be suitable by 2071–2100.[27] There is no equivalent work on dengue in *A albopictus*, which is the more likely vector to enter the UK. Transmission of dengue virus by *A albopictus* continues to be reported in parts of the Mediterranean (ie, France and Croatia).

First reports of the establishment of *Aedes japonicus* in Europe were in northern Switzerland, and the species has now spread to large parts of western Germany[28] and has established localised populations in Belgium and the Netherlands.[14] The role of *A japonicus* as a vector is being debated, with some experimental evidence of vector-competence for the West Nile virus. *A japonicus* is likely to survive in a British climate and to be imported through the same pathways as *A albopictus*.

West Nile virus and other arboviral infections

West Nile virus is one of several bird-associated viruses transmitted by mosquitoes. Since 1999, outbreaks of West Nile virus in the USA have caused more than 39 000 reported human cases and more than 1600 deaths.[29] Outbreaks have also occurred in Europe, with more than 700 cases reported in 2013.[30] West Nile virus is transmitted by several European mosquitoes, many of which are found in the UK. The main vectors are the human-biting *Culex* species. The abundance and activity of mosquito vectors of West Nile virus are very sensitive to changes in temperature,[31] and increasing temperature is considered to be one of the drivers of its emergence in Europe.[32]

There are 34 different mosquito species in the UK,[33] the numbers of which are highly responsive to changes in temperature and precipitation.[34] Increased summer temperatures (as predicted by climate change) promote mosquito development and increase their abundance. Seasonal rains provide additional aquatic habitats necessary for larval development.[35] Summer flooding or rewetting after summer drought can increase UK mosquito numbers substantially, and management of floodwaters and groundwater is crucial in determining mosquito abundance.[33,36] Birds are likely to import the virus into the UK, where local mosquitoes might act as vectors.[33] There is some evidence[37] of antibodies to West Nile virus in UK-resident birds, but so far, no local human cases have been reported. This might be explained by a restricted distribution of species of resident human-biting *Culex* species (ie, bridge-vectors for the virus). However, in 2010, *Culex modestus* (an important West Nile virus bridge-vector) was found to be established throughout the North Kent marshes of England and continues to increase in dominance in the area, with some evidence of spread.[38–40]

In addition to the effects of changes in climate, it is important to consider the effects of adaptation to climate change. Climate-change adaptation and EU regulation are driving the creation of new wetlands and restoration of existing wetlands in the UK. The initiatives include the re-alignment of coastlines to mitigate storm surges and sea level rise, the creation of new urban wetlands (sustainable urban drainage, sewage treatment reedbed), often as part of ecological mitigation, and the expansion of wetlands through arable reversion. These initiatives aim to provide better flood alleviation and new habitats for wildlife; however, they will probably increase the available habitat for mosquitoes and might increase the risk of subsequent transmission of mosquito-borne disease.[41] Public Health England has done several studies[36,42,43] of the effect of these new wetlands on mosquitoes and is developing guidance for the Environment Agency and wetland managers on how risks can be mitigated during a disease outbreak. New wetlands are clearly creating habitats for mosquitoes, but with an understanding of mosquito ecology, targeted wetland-management approaches might be an option to control mosquito habitats. Consideration is now given to how flood management and wetland creation schemes might affect public health through nuisance biting or disease risk. The findings of these studies suggest that ideally, new habitats designed as part of climate-change adaptation should be assessed in terms of environmental effect and future disease risk from mosquitoes and should include plans to mitigate nuisance or vector mosquitoes, and that such an assessment should be made on a case-by-case basis.[44]

One of the key effects of climatic change is extreme weather. Drought is known to be a contributory factor to outbreaks of the West Nile virus in North America.[45] As wetlands dry, the remaining pools become hubs of bird activity, which, coupled with the increase in abundance of mosquitoes developing in nutrient-rich waters, increases the animal-vector interface that drives virus transmission.[46] Furthermore, there is good evidence[36] that unnatural drying of aquatic habitats due to drought leads to high mosquito abundance after re-wetting, owing largely to the negative effect of drought on mosquito predators and competitors. Flooding can also create additional aquatic habitats and thereby contribute to mosquito-borne disease risk. However, flooding can also flush aquatic habitats and make them inimical. Mid–late summer flooding can increase available habitat for open grassland floodwater mosquitoes, whereas winter or spring flooding is more beneficial to woodland mosquitoes.[36] Unpublished data from mosquito surveys in the Somerset Levels of the UK during the 2014 floods showed no evidence of mosquito issues, and this was largely due to the water draining before the mosquito season. Timing and length of flood events is probably important in determining mosquito diversity and abundance. There is still a need for a better understanding of the effects of extreme weather, or rather this climatic variability, on disease vectors in the UK. Field-based evidence will be important to properly inform risk assessment and preparedness plans.

One mosquito species that is particularly responsive to flooding in parts of central Europe is *Aedes vexans*.[47] *A vexans* is the primary vector of the Rift Valley fever virus in Africa. Despite the mosquito's occurrence in Europe, no outbreaks of Rift Valley fever virus have occurred. In the UK, *A vexans* is considered rare, although further field studies are needed to investigate its current status.

Malaria

Malaria was endemic to parts of the UK during the 19th century, with isolated outbreaks in the 20th century after the return of infected servicemen. *Plasmodium vivax* malaria recently returned to Europe, with ongoing local transmission in Greece.[9] The UK still has several competent malaria-vector mosquito species, with a suitable climate for *P vivax* and, to a lesser degree, *Plasmodium falciparum* malaria.[9] The parasite undergoes a temperature-dependent obligatory development phase in the mosquito. With rising summer temperatures, this rate of development for malarial parasites will shorten, thus increasing the chances for transmission.[9] However, malaria is not zoonotic (ie, does not rely on an animal source), and infected people would need to be exposed to nuisance anopheline mosquitoes for transmission to occur. Caminade and colleagues[4] have analysed the effect of climate change on *P falciparum* malaria, using four emission scenarios that predict about 1·5°C increase in temperature by 2030 and between 1·5°C and 5°C increase in temperature by 2100. The probability of sustained *P falciparum* transmission by 2100 is small, even under the most extreme scenario. However, one of the five models of malaria under the most extreme scenarios consistently predicts that the climate in southern England will be suitable for sustained *P falciparum* transmission (lasting >1 month) by 2080, whereas one model also predicted some suitability by 2030. However, the other models predict no suitability, even by 2080. By contrast, under a scenario of medium–high level of climate change severity, a *P vivax* model by Lindsay and colleagues[9] predicted 2 months of climatic suitability in southern Great Britain and 4 months of climatic suitability in parts of southeast England by 2030. Results of yet another study[10] predicted that by 2080, regions as far north as southern Scotland will be climatically suitable for 2 months and southern Great Britain will be climatically suitable for 4 months. The incidence of anopheline biting of human beings is very localised[33] and transmission is therefore unlikely to be widespread. Furthermore, the availability of antimalarials and the current health-care system should minimise risks from malaria in the UK.[2]

Ticks and tick-borne disease

The UK has 20 endemic tick species, the most common being *Ixodes ricinus* (deer or sheep tick). This species is the principal vector of Lyme borreliosis, also known as Lyme disease, which causes more than 1000 confirmed human cases each year, with many more unreported. Several other tick species bite human beings, and a few might also be involved in disease transmission.[48]

Lyme disease and *I ricinus*

A recent EU-wide review[11] of the change in distribution of *I ricinus* reported several climatic, land-use, and ecological factors underlying its increased densities and expansion in geographical distribution. There is good evidence that *I ricinus* is increasing its distribution latitudinally in parts of Scandinavia[49] and altitudinally in the Alps[11] (table). EU climate models[50] suggest that the range of *I ricinus* in Europe might double. In the UK, *I ricinus* already occurs as far north as northern Scotland (figure 3).[48] In the Alps, *I ricinus* has increased in altitudinal spread by 400 m in the past three decades. In Scotland, ticks occur at up to 700 m altitude.[51] Some expansion to higher ground can be expected, although ticks are far more abundant at lower altitude. The main drivers for spread of ticks in lowland UK are the increasing numbers and spread of deer (principally roe and red deer),[52] the expansion of towns and cities into the green belt (a ring of countryside normally restricting expansion of urban areas), and movement of deer into urban areas.[2,11] The Public Health England tick surveillance scheme[48] reported an increase in tick problems in urban areas, which might be exacerbated

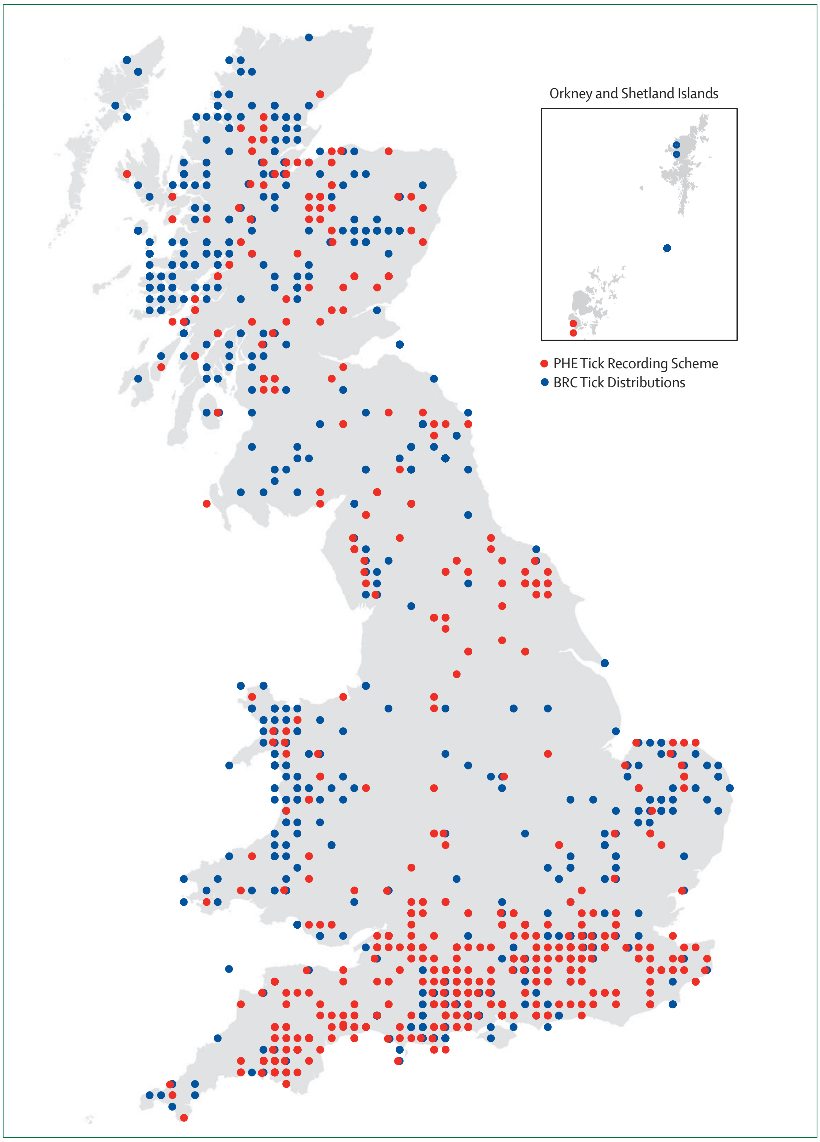

Figure 3: **The distribution of *Ixodes ricinus* in Great Britain, as recorded by the Public Health England Tick Recording Scheme and the Biological Records Centre**
PHE=Public Health England. BRC=Biological Records Centre. Red dots show records between 2005 and 2013, blue dots show all historical data before 2001. Areas with only red dots show evidence of possible recent expansion in the distribution of *I ricinus*. Source: Public Health England

by climate-change adaptation strategies to promote urban greenspace (mitigation for urban heat islands) and wildlife corridors in urban and rural areas, with tick-infested wildlife moving into these green spaces and through these corridors. Urban cases of Lyme disease are being reported at an increasing rate in the UK. Local authorities need to develop plans to mitigate tick issues through environment and greenspace management and tick awareness strategies.[2] It needs to be borne in mind that *I ricinus* ticks have three active stages (larvae, nymphs, and adults) and each stage feeds on a range of animal hosts. Small mammals tend to be infested mostly by larvae. Nymphs are found on a range of hosts, including squirrels and woodland birds. All stages, including adult ticks, infest large animals, such as livestock and deer, and the presence and abundance of these large hosts often determine the survival of tick populations. The seasonal variation in host infestation by ticks varies between animals and geographical location. The additional variability of microclimate in the microhabitats in which ticks spend much of their lifecycle in (ie, within vegetation), makes any assessment of likely change in the distribution and abundance of *I ricinus* because of climate change somewhat problematic.

Lyme disease cases are increasing in the UK each year, and wildlife movement and land-use changes might continue to exacerbate the incidence. However, changes in weather, particularly extreme weather, will affect tick activity and abundance.[53] *I ricinus* is acutely responsive to humidity and temperature. Hot, dry summers are unsuitable for this tick species and force it into summer quiescence. By contrast, mild, wet winters might prolong winter tick activity, and warmer springs will lengthen the period of tick activity and increase tick densities.[2] Human behaviour also changes as a result of a warmer climate; as people spend more time outdoors, wearing fewer clothes, with consequent exposure to ticks and Lyme disease potentially increasing.

Borrelia burgdorferi sensu lato, the pathogen transmitted by *I ricinus* and the cause of Lyme borreliosis, cycles between ticks and several wild animals (eg, mice, voles, squirrels, woodland birds, and pheasants), and the effect of climate change on each individual animal will affect pathogen prevalence rates in complex ways.[54,55] Furthermore, the different strains of *Borrelia* out-compete each other, making an assessment of climate change on Lyme borrelia prevalence in ticks difficult to predict. Game and habitat management (ie, pheasant, deer) is more likely to have a greater effect on prevalence than climate alone. Nevertheless, a more favourable climate that increases tick densities could increase the exposure of people to infected ticks. In the case of habitats, there is some evidence that woodland management strategies could be harnessed to minimise the exposure of people to infected ticks.[56] However, areas with high tick densities do not always have high borrelia infection rates in ticks because large animals (eg, deer, livestock) that sustain high tick abundance can act to dilute the infection rates of borrelia within ticks.

In central Europe, *I ricinus* is known to transmit tick-borne encephalitis virus. Climate change models suggest a northern spread of tick-borne encephalitis virus, but this is not expected to affect the UK.[57] However, a similar virus (louping ill virus) already occurs in the UK, but the public health risks of this virus remain unclear. Furthermore, several studies[58–60] have addressed the presence of other potential tick-borne pathogens (eg, rickettsiae, *Borrelia miyamotoi*) in *I ricinus*, as well in *Dermacentor reticulatus* and *Haemaphysalis punctata*, but again, the importance of these possible pathogens to public health needs further investigation.

Exotic ticks

Since the relaxation of tick controls on travelling pets, the Public Health England tick surveillance scheme now reports an increase in the importation of the dog kennel tick *Rhipicephalus sanguineus* on dogs from other parts of Europe.[61] This species is a known vector of spotted fever rickettsiosis (*Rickettsia conorii*), and although the UK climate is currently considered inimical for survival of this tick outdoors, this pattern could change.[13] Nevertheless, this species can infest homes and kennels and become a nuisance and a disease risk indoors.[62,63] *R sanguineus* is also often reported on dogs imported commercially and by dog rehoming charities. The lack of active surveillance and the relaxation of tick treatments will probably result in this tick becoming endemic to the UK (at least as an indoor pest).[2,61] Because this tick is not so sensitive to reductions in humidity, increased summer temperatures will favour its survival. A 2–3°C increase in mean temperature from April to September is expected to result in its establishment in regions of northern temperate Europe.[64] Although no specific modelling of climate suitability across Europe with climate change exists, findings of a French study[65] showed that between 1960 and 2000, *R sanguineus* theoretically extended its range by 66%, gaining 130 000 km², including parts of northern France. However, owing to its endophilic (indoor) and monotrophic (able to feed on one animal throughout all stages of development) nature and an ability to produce four generations each year, its establishment indoors is possible in regions where climate would not otherwise permit its survival. With an increased incidence of inadvertent importation of this tick into the UK on dogs, reports of homes infested with *R sanguineus* will become more common.

Another exotic tick species, *Hyalomma marginatum*, is imported into the UK on migratory birds each year. *H marginatum* is the principal vector of Crimean-Congo haemorrhagic fever virus in eastern Europe. At present, UK climate is considered too cold for its survival, but with climate change, this tick is expected to survive and become established.[66] Field studies at bird observatories in the UK show high rates of importation of this tick on spring migrant birds,[67] but there are still no reports of established populations.

Sandfly-borne disease

Phlebotomine sand flies are not established in the UK, although results of EU reviews and models[68] show an actual and expected northerly spread of their range from southern Europe. Sand flies transmit *Leishmania* spp parasites in the Mediterranean region, and there is some evidence that their distribution is changing,[69] although current transmission of leishmania parasites by sand flies in the UK is unlikely.

Conclusion

Although not identified in the UK, the UK climate at present could support 4–6 months of *A albopictus* mosquito activity; however, abundance would probably be low, compared with areas of southern Europe. A 2°C temperature rise could extend this hypothetical season by 1 month and increase the geographical area of suitability by 25–30%. On the basis of the assumption that competent vectors exist, a 1 month period of chikungunya transmission could be possible in London by 2041, with 1–3 months of activity a possibility in southeast England by 2071–2100.

At present, the UK climate does not support establishment of *A aegypti* and is not expected to suit *A aegypti* establishment before 2100. Therefore, transmission of dengue in the UK by this mosquito is not anticipated, even with a 2°C temperature rise. However, *A albopictus* is a competent vector of the dengue virus and is responsible for cases in Europe, and any changes to the virus to allow for increased vector capacity should be considered. Models that incorporate the risk of dengue from *A albopictus* are now needed.

The UK climate is considered suitable for the transmission of West Nile virus, although no transmission is known to have occurred so far. Limiting factors probably include low mosquito abundance and limited distribution of human-biting *Culex* spp. A 2°C temperature rise would affect mosquito abundance substantially by shortening periods of blood digestion, gonotrophic development, and immature development. Furthermore, the expansion of *C modestus* in Kent[38–40] might provide a suitable bridge vector for transmission, and further studies on this species are necessary. Climate-change adaptation strategies that involve enlarged wetlands might also exacerbate the risk.

Panel: Recommendations

- Continue to enhance UK surveillance of endemic and non-native vectors through enhancement of existing passive vector surveillance schemes, maintenance and expansion of existing trap networks across the UK, and targeted surveillance for the incursion of non-native invasive vector species
- Reach a better understanding of the effect of climate-change adaptation strategies on vectors and vector-borne disease, and develop strategies to deal with changing public health risks in a changing environment, such as wetland management strategies and wetland creations; wetland creation health impact assessment for mosquitoes; and habitat-specific and urban greenspace management to reduce tick exposure and Lyme disease risk
- Reach a better understanding of the effect of extreme weather events (eg, flooding, drought) on risk of infectious disease, and work with environmental organisations to develop vector management plans and forecasting methods to prepare for a disease outbreak resulting from an extreme event
- Develop, where possible and appropriate, improved models that incorporate the many drivers for change (including climate) for a range of vector-borne diseases; in addition to climate-based models, vector models should focus on land-use and its change and host distributions and abundance
- Continue to work collaboratively across Europe in sharing data on vector-borne diseases and disease vectors, and ensure that risk assessment includes the effects of climate change and adaptation; collaborative work includes the contribution to European-wide vector surveillance strategies and consideration of vector-related risk in European-wide biodiversity enhancing strategies

Search strategy and selection criteria

We searched PubMed, Google Scholar, and Web of Science, for all papers up to Oct 1, 2014. Search terms were related to vector-borne disease in Europe, vector (mosquito, tick, sand fly) in the UK, present or historical occurrence of vector-borne disease in the UK, and climate change assessments and vector-borne disease. Although all references to vector-borne disease in Europe were considered, the focus was given to reports of potential relevance to the UK, either now or in the future, in view of expected changes in climate or extreme weather. Each search combined terms related to pathogen or vector and "climate" or "weather".

The present climate could support transmission of *P vivax* malaria, and to a lesser degree, *P falciparum* malaria, although no cases are currently reported. Limitations to the transmission of *P vivax* are low rates of anopheline biting of human beings, the absence of a zoonotic source, and the availability of drugs for malaria. Climate change could support more than 1 month of *P falciparum* transmission by 2080, 2 months of *P vivax* transmission by 2030, and 4 months of *P vivax* transmission by 2080.

Lyme disease is already endemic across large parts of Europe including the UK. There is evidence that climate is affecting altitudinal and latitudinal spread of the *I ricinus* tick vector in Europe, although this spread is probably not so pronounced in the UK, where ticks occur throughout and at an altitude of up to 700 m. Rising temperatures will affect seasonality of ticks, and other landscape change factors and urban greenspace might exacerbate human exposure to ticks. However, the effects of climate on infection rates of borrelia in ticks need to be considered.

Climate change models do not predict incursion of tick-borne encephalitis virus in the UK, although *I ricinus*, the tick vector, is present and abundant.

Exotic tick species, such as *H marginatum* (vector of the Crimean-Congo haemorrhagic fever virus), imported on migratory birds, and *R sanguineus* (vector of rickettsiosis), imported on dogs, are limited by the UK climate and do not survive outdoors. However, this ability to survive might change with a 2°C rise in temperature. *R sanguineus*, imported in large numbers on untreated dogs returning to the UK, can survive indoors.

There is little doubt that climate change will affect vector-borne disease risk. However, climate change will not be the sole factor in changing the epidemiological picture of vector-borne disease in Europe, and it is generally inappropriate to make assessments of the effect of changing temperature alone on disease, particularly vector-borne diseases. Other factors of equal importance include socioeconomic development, urbanisation, land-use change, climate change adaptation, migration, and globalisation. Quantification of the effect of climate change on vector-borne disease and the risk it poses to public health is therefore very difficult to assess. Importantly, consideration must be given to the capacity of public health systems worldwide to adapt to the infectious diseases that might result from climate change. This ability to cope with infectious diseases will be a major factor in the assessment of the effect of climate change on public health in Europe (panel).

Contributors
JMM did the literature search and edited the table. JMM and SAL extracted and interpreted the data and wrote the manuscript.

Declaration of interests
We declare no competing interests.

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