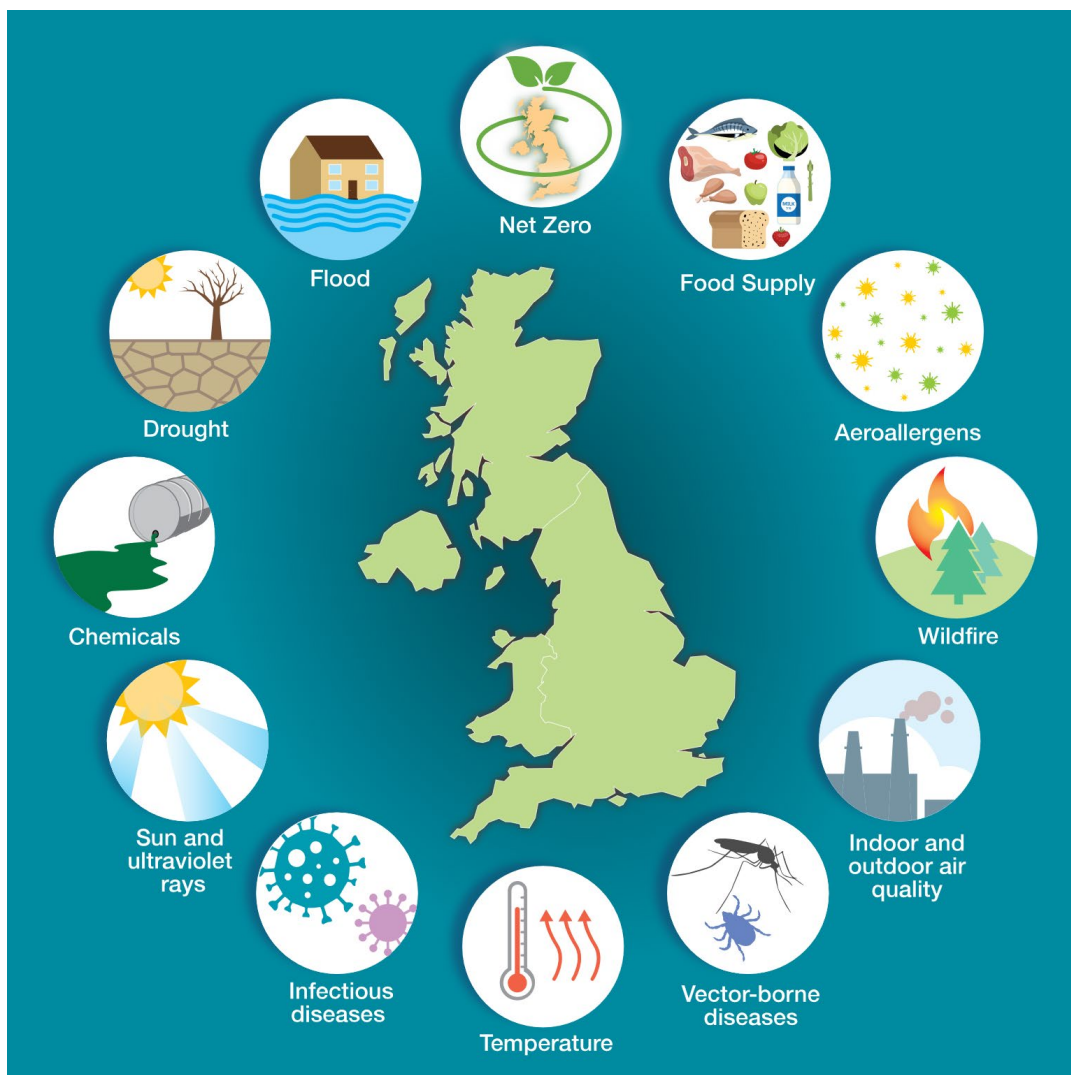




UK Health
Security
Agency

Health Effects of Climate Change (HECC) in the UK: 2023 report

Chapter 8. Direct and indirect effects of climate change on vectors and vector-borne diseases in the UK



Summary

Vector-borne diseases (VBDs) are highly climate sensitive, and the risk from these infections will change in the UK in the context of climate change. This chapter presents an assessment of mosquito and tick vectors of public health importance in the UK, and how they may change in the future. It includes new empirical analyses conducted by the UK Health Security Agency (UKHSA) and partners from the Centre for Ecology and Hydrology and the University of Liverpool. The analyses in this chapter use a high end warming scenario consistent with approximately 4.3°C of warming. These projections of VBD risk are therefore worst-case scenario estimates in the absence of climate change mitigation and adaptation.

Weather and climate are well-recognised drivers of tick and mosquito (vector) presence, distribution and seasonality. Warmer temperatures are leading to expansion of the geographical range and seasonal duration of vector activity. Weather and climate can also affect the pathogens carried by these vectors, as well as other non-climatic drivers such as vector habitat. As a result, VBDs are influenced by climate and weather both directly and indirectly through several pathways.

There is potential for warming to increase the UK distribution of several tick species of public health importance, including *Ixodes ricinus*, which can transmit Lyme disease (Lyme borreliosis) and tick-borne encephalitis (TBE). Lyme disease incidence is already increasing in the UK and although the risk of TBE is currently very low, there have been a small number of TBE detections in the UK since 2019. Increases in these 2 infections are the most likely emergent tick-borne risks in the UK as the climate warms.

A concern under warming temperatures is the potential introduction and establishment of invasive mosquito species in the UK, particularly *Aedes albopictus*, an aggressive daytime biting mosquito species that can transmit several arboviruses of public health concern, including dengue, chikungunya and Zika. Climate modelling suggests that the area around London already has a suitable climate for *Ae. albopictus* survival, and most of England will become suitable for its establishment by the 2040s and 2050s. Under this reasonable worst-case scenario, by the 2060s or 2070s, most of Wales, Northern Ireland and parts of the Scottish Lowlands could also become suitable. It is expected that London could become suitable for endemic dengue transmission as early as the 2060s under a high-warming scenario. Similarly, high-warming scenarios indicate the potential suitability for chikungunya transmission in the UK beginning in the latter half of the century, with spread linked to rate of warming. This evidence indicates that the establishment of *Ae. albopictus* in the UK is one of the most significant risks for public health posed by climate change.

Climate change will also increase the risk of West Nile virus (WNV) in the UK. To date there have been no cases of this infection acquired in the UK. The virus is carried by *Culex* mosquitoes, including *Culex modestus*, which is now established in coastal parts of south-east England. While current UK temperatures are generally too low for WNV transmission cycles to

be established, projected warming will increase the risks of WNV outbreaks, with epidemics possible by the second half of the century and south-east England is the area most at risk.

The chapter highlights 3 public health insights for the implications of climate change on VBD. Firstly, once a non-native vector species is established, it is difficult for it to be eliminated, highlighting the critical role of early and robust vector surveillance and control. Secondly, early indications of emergence into the UK of vector species and new pathogens are already apparent: localised detection of invasive *Ae. albopictus* in the UK in recent years and increasing reports of small outbreaks of dengue, chikungunya and Zika in Europe are examples of early indicators of rising risk. Information and guidance for the public should raise awareness of these risks and promote behaviour changes to protect health and minimise risks. Lastly, the public health implications of changing VBD risks and introduction of the nuisance mosquito *Ae. albopictus* are significant and may necessitate changes to building design (such as screens on windows and doors), substantial shifts in public behaviour to avoid bites and increased awareness among frontline and diagnostic health services.

Several research gaps and priorities have been identified in this chapter to inform action to control the risk from VBD, including the need to:

- advance the development of UK-specific modelling capacity of VBD risks through provision of climate scenarios at sufficient resolution to allow health impact assessment for a range of warming scenarios
- strengthen surveillance including sero-surveillance capacity and research to promote early and rapid detection of emerging vector-borne pathogens
- assess the impact of significant land-use changes and environmental policies on VBD risk using field-based studies
- develop evidence-based guidance for greening, 'rewilding', nature-based approaches, and other significant land-use change strategies to promote multiple health benefits, balancing risk of VBDs with other health considerations

UKHSA monitors tick and mosquito populations through both passive and active surveillance activities, and also monitors for non-native vectors. UKHSA has contributed to developing a cross-government contingency plan following the detection of invasive mosquitoes in England, which involves a network of invasive mosquito trapping locations coordinated by UKHSA. In addition, UKHSA is a member of the Human Animal Infections Risk Surveillance (HAIRS) group, which is a multi-agency cross-government horizon scanning and risk assessment group, aiming to identify and risk assess emerging and potentially zoonotic infections which may pose a threat to UK public health.

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Chapter 8. Direct and indirect effects of climate change on vectors and vector-borne diseases in the UK

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1. Introduction

Vector-borne diseases (VBDs) are caused by infections with parasites, viruses and bacteria which are transmitted to humans and animals by blood-feeding arthropods (vectors), such as mosquitoes, ticks, midges, sand-flies and fleas. As arthropod vectors are ectothermic, changes in weather and climate can directly affect the biology of vectors and the pathogens they transmit. Precipitation is vital to vector survival: mosquitoes have aquatic developmental stages and relative humidity is also vital to the survival of certain tick species. Warmer temperatures result in faster vector development, increased survival, and increased biting rate of vectors up to a threshold, with increased mortality occurring if temperatures are too high. In addition, the rate of pathogen development within mosquitoes, known as the extrinsic incubation period, generally accelerates under warmer temperatures to a certain threshold, increasing the rate of disease transmission, as well as reducing the fitness of the vector, thus changing its behaviour. Vector distribution can also alter with climate change: regions may become unsuitable for vectors due to increasing temperatures or reduced precipitation. Similarly, regions historically unsuitable for vectors, including higher altitudes and latitudes may become suitable, exposing naive populations to VBDs.

Whilst climatic changes will undoubtedly affect vectors and VBDs, there are several other factors that play a role. Trade and travel increases importation risks of non-native vectors and pathogens; land use changes, including those intended to mitigate the effects of climate change and increase biodiversity, can create or destroy vector habitats, and urbanisation of rural greenspace or greening of cities can bring people into close or more frequent contact with vectors; animal movements can introduce ticks into new areas, including cities; socio-economic conditions, including access to health care, as well as changes in human behaviour can increase exposure to vectors and VBDs. To increase this complexity, climate can also indirectly impact vectors and VBDs in several other ways, including affecting food sources for wildlife that act as blood-hosts and changing host activity patterns, interactions, and distributions. It is thus important to consider how these factors influence vectors and VBDs in a changing climate, both by considering the direct effects of climate change, but also by understanding the indirect effects and environmental changes that make quantifying the direct comparisons of climate and vectors so challenging, and in untangling their interactions.

In the first 2 iterations of the 'Health Effects of Climate Change in the UK (HECC)' report published in 2002 and 2008 ([1](#), [2](#)), the chapters on VBDs focused predominantly on the risk of malaria, Lyme borreliosis and tick-borne encephalitis virus (TBEv) in the UK in future. In the third iteration of the report, the chapter discussed the risk of non-native vectors including the risk of establishment of *Aedes albopictus*, the effect of land use changes on vectors as well as the risk of future malaria transmission in the UK. Since the publication of the last iteration of the HECC report in 2012 ([3](#)), there have been several detections of non-native vectors in the UK, including non-native ticks biting people ([4 to 8](#)) and animals ([9 to 12](#)), as well as detections in homes ([13](#)). There have been detections of pathogens not previously seen in the UK, such as *Borrelia miyamotoi* ([14](#)) and TBEv ([15](#)). In addition, there have been multiple detections of

invasive mosquitoes in England ([16 to 18](#)). Several climate-sensitive zoonotic pathogens and vectors are increasingly being reported in the UK associated with imported dogs, in particular with dogs adopted from southern Europe. Mosquito-borne dirofilariasis and sand-fly borne leishmaniasis are now being reported by veterinarians in dogs that have come from southern Europe, including in some with no travel history. The UK currently has mosquitoes that can act as vectors of *Dirofilaria*, but so far has no phlebotomine sand-fly vectors of *Leishmania*, although that may change with a warming climate. These risks sit alongside the incursions of *Rhipicephalus sanguineus* ticks and other imported tick species on travelled and adopted dogs, thus highlighting this risk pathway as a significant concern for future incursions of disease vectors and climate-sensitive vector-borne pathogens.

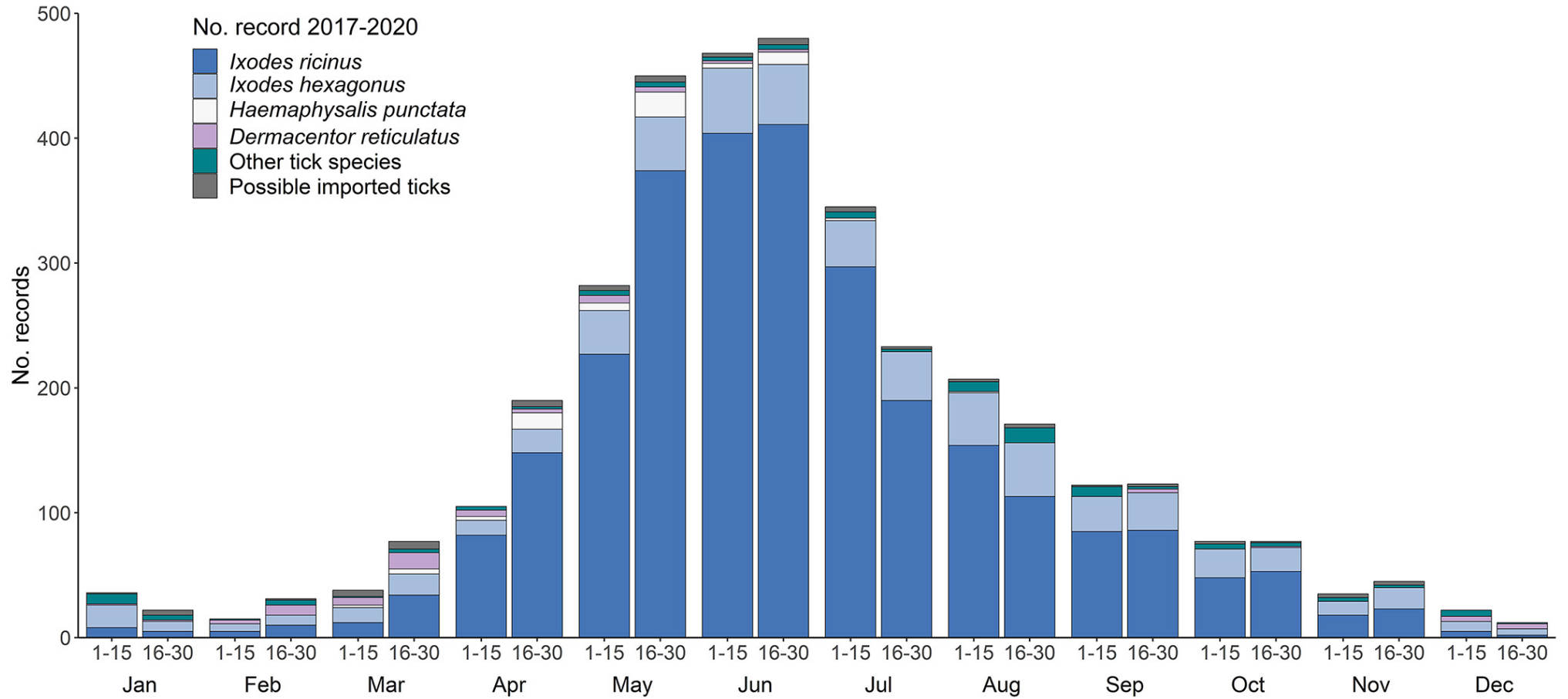
Here, we have updated the evidence base for the direct and indirect effects of climate change on vectors and VBDs in the UK by reviewing the key issues related to ticks and mosquitoes. We have updated modelling that was included in the previous HECC report ([3](#)), using the most recent climate projections data from the Met Office (UKCP18). New modelling examining the possible risk of non-native vectors and pathogens becoming established in future has also been included, with discussion around public health implications for the UK.

2. Ticks and tick-borne diseases

The survival, distribution and density of ticks is determined by 3 key elements: microclimate, habitat and hosts, all of which can be impacted by climate change. The public health risk from ticks is further influenced by human behaviour (including precautionary behaviours) and the way in which we access and manage the environment where ticks or key tick hosts are found (19). The UK has over 20 recorded tick species (Acari: Ixodidae). Many are specialist ectoparasites of wildlife and thus are of little concern for public health. Several species, however, are more general in their host associations, such as *Ixodes ricinus*, or are associated with domestic animals and livestock (*Dermacentor reticulatus*, *Haemaphysalis punctata*) and are most often associated with veterinary pathogens but can also be an emerging public health concern. Occasionally, non-native species, such as *R. sanguineus* and *Hyalomma marginatum* may occur in the UK; whilst detections of these species is rare, their ability to establish outdoors in the UK is very much climate dependent, as higher temperatures are required for their development.

Since 2005 there has been a Tick Surveillance Scheme (TSS) covering the UK, run by medical entomologists at the UK Health Security Agency (UKHSA, previously Public Health England (PHE) and Health Protection Agency (HPA)). The data is based on submissions from the public, clinicians, veterinarians and those working with wildlife. Although a voluntary passive surveillance scheme, it provides the best available data set on UK tick distribution and the best assessment of where ticks are causing human and animal biting concerns. *Ixodes ricinus* accounts for approximately 77% of all records, followed by *Ixodes hexagonus* (mostly from pets), with *D. reticulatus* and *H. punctata* accounting for fewer than 4% of records. Submissions of ticks occur throughout the year, including during winter, with most submissions occurring during the summer months (Figure 1).

Figure 1. Seasonality of tick record submissions to the Tick Surveillance Scheme (TSS) by species during 2017 to 2020 (20)

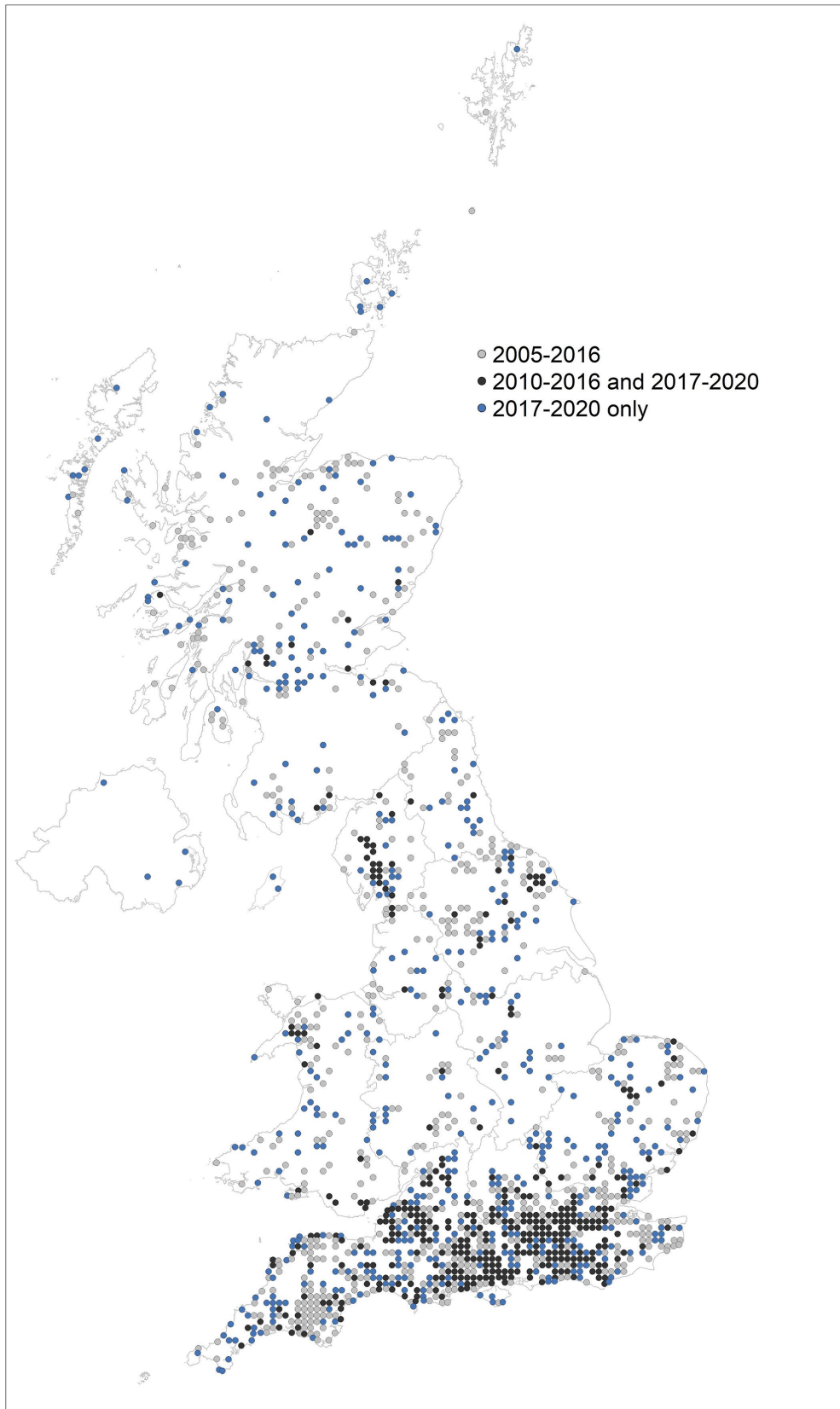


2.1 Native UK ticks: *Ixodes ricinus*

Ixodes ricinus is the most common tick species in northern and central Europe. It is found in many different habitats, including woodland, heathland, grazed and scrub grassland, urban parks and gardens. There are 3 free-living stages of *I. ricinus*: larva, nymph and adult. All 3 life stages feed on a range of animals, including small mammals (although rarely infested by adults), woodland birds, game birds such as pheasants, deer and livestock. Only a small percentage of each life stage is spent on the host; most of the development and activity takes place off-host under the direct influence of the microclimate. Thus, the distribution of *I. ricinus* is limited to areas of moderate to high rainfall, with good vegetation cover and where the soil surface remains humid (80% or higher) during dry periods ([21](#)).

Data from the TSS suggest that *I. ricinus* is widely distributed in the UK (Figure 2). In England, *I. ricinus* is particularly common in southern counties, with key endemic foci also in East Anglia, Yorkshire and Cumbria. In Wales, records are more disparate, with most records from areas of western Wales. Records from Scotland probably under-represent the true distribution; however, many of the Highland glens, islands, parts of the central belt and Galloway have populations of *I. ricinus*. Northern Ireland is sparsely represented in the Scheme, and further study is needed to establish the true extent of *I. ricinus*, particularly as recent work not associated with the TSS has identified the extensive distribution of *I. ricinus* in the Republic of Ireland ([22](#), [23](#)).

Figure 2. Distribution of records of *Ixodes ricinus* in the UK mapped at 10km resolution
Grids with *I. ricinus* presence reported between 2005 to 2016 only are light grey. Those in dark grey had records during 2010 to 2016, and 2017 to 2020 and represent persistent reporting of this species in these areas. Grids in blue have records of *I. ricinus* reported for the first time during 2017 to 2020 and may indicate new areas of distribution ([20](#)).



2.1.1 Impacts of climate on the distribution of *Ixodes ricinus*

Range expansions have been observed or predicted for *I. ricinus* (24 to 26). Specifically, *I. ricinus* has been previously reported at 1,020 to 1,650 metres above sea level in the Alps (27, 28), but established populations have been more recently reported at 1,700m, and there have been one-off records up to 1,890m (29). In addition, ticks found in more northern latitudes such as Iceland (30), and increases in tick bite reports (species unknown) in northern Russia between 2000 and 2018 have been linked to warmer temperatures (31).

Models investigating the potential change in distribution of *I. ricinus* in Europe under projected climate scenarios suggest high certainty of increase of *I. ricinus* in the European Alps, an extension in the distribution across most of Europe, as well as predicted expansion into new areas in Northern and Eastern Europe previously considered unsuitable for survival (26, 32). A model focusing on Scotland found that regional warming could lead to disease risk occurring further northwards and at higher altitudes in future (33).

2.1.2 Impacts of climate on the phenology of *Ixodes ricinus*

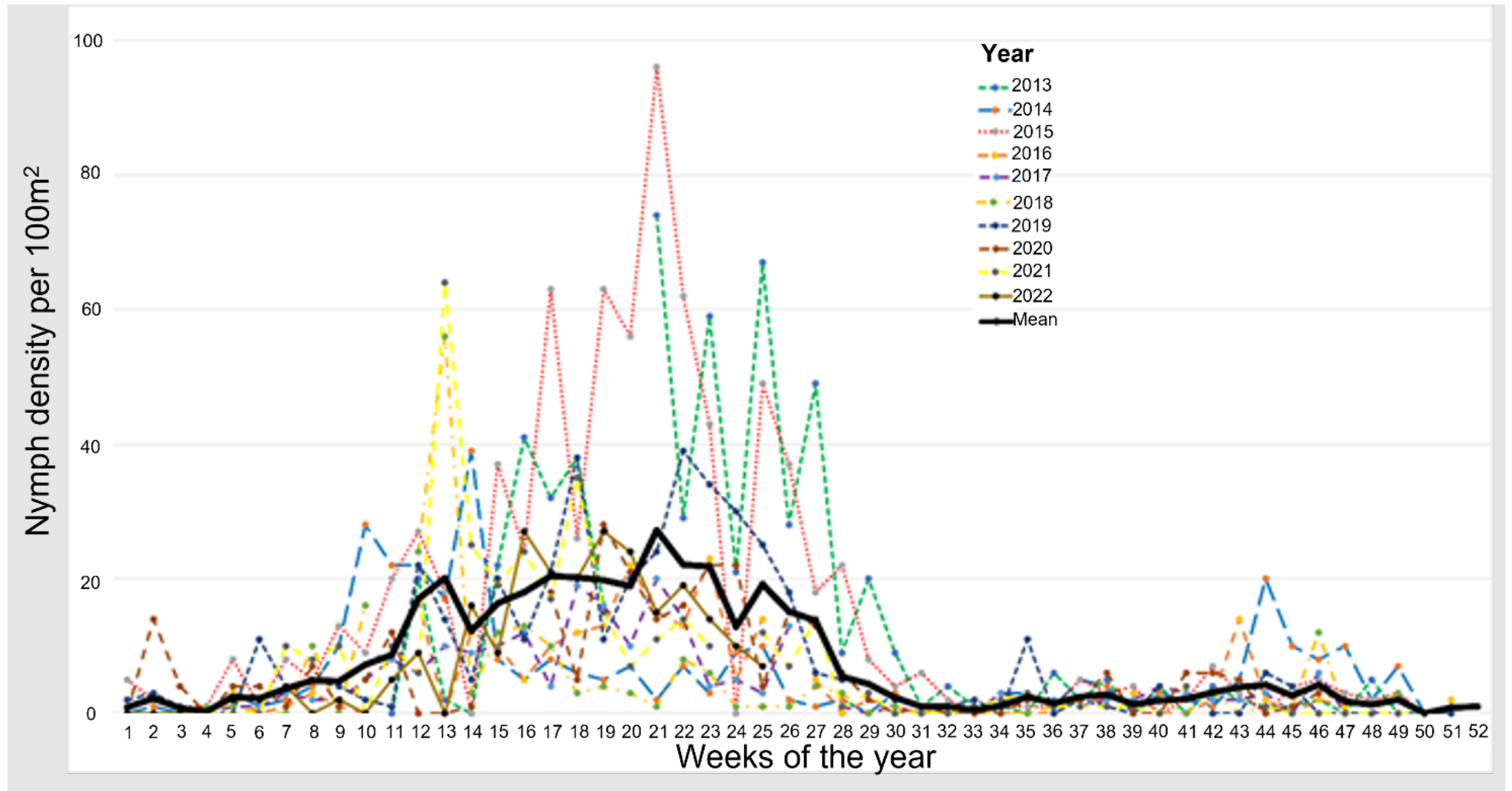
There are several weather parameters that are known to affect *I. ricinus* phenology and abundance, such as temperature, relative humidity, saturation deficit (a measure of the drying power of the atmosphere integrating both air temperature and relative humidity), precipitation and sunshine hours (also termed photoperiod or day length).

Temperature is one of the most important parameters; in general, *I. ricinus* questing begins when air temperature exceeds 7°C (34) and warmer-than-normal temperatures during spring resulted in an earlier onset of tick activity (35). Increased numbers of both questing and feeding ticks have been associated with warmer temperatures (36 to 41). Some studies have reported a negative effect on questing ticks when temperatures were warmer than normal, which was linked to increased saturation deficit levels reducing survival (42, 43), although a field study in Ireland found that all stages of *I. ricinus* remained active when temperatures reached 35°C if there was adequate vegetation for rehydration (44).

Field studies across Europe have reported peaks in *I. ricinus* nymph activity between March and June (45 to 50), with a second, smaller autumnal peak reported by some but not all studies (39, 41, 45 to 49). Such bimodal tick activity is thought to be driven by highly seasonal climates, with a single spring peak observed in regions where there is less climatic variation between seasons (45, 51). In addition, hot, dry summers may increase tick abundance in autumn and early winter, resulting in a shift in activity from spring to autumn for a large proportion of the tick population (52). In the UK, weekly surveys of *I. ricinus* activity have been conducted in a woodland in southern England since 2013 (Figure 3), totalling 443 weekly surveys of 10m x 10m transects. Nymphs remain active through the winter, although at a lower density. On average, nymph densities start to increase around late March (week 12) and remain high until end of June (week 26), when a sharp decline is seen. There is very little evidence for a notable second peak during the autumn, although small secondary peaks occurred during 2016 and 2018, whilst a more significant second peak was seen during 2014.

Figure 3. Density of nymphs per 100m² in a woodland in southern England during 2013 to 2022

Each year is represented with a different line, the thick black line represents the mean across all years (UKHSA, unpublished data).



Laboratory experiments suggest that under future climate scenarios, the activity season of *I. ricinus* populations could advance by a month (earlier) in spring, and based on temperature alone, at least 20% of active nymphs in southern England would be able to quest at any one time over the whole year (53). Late winter and early spring in Scotland would no longer be disease risk-free as temperature increases of 3°C would increase tick survival and a higher proportion of questing ticks would become active earlier in the spring and later in the winter (33). During the 2006 to 2007 winter in Germany, mild conditions (approximately 4.6°C warmer than the long-term average) resulted in continuous questing of *I. ricinus* nymphs and adults throughout the winter (54). Such changes could result in increased tick-host contact during periods currently considered unsuitable for tick survival, and thus a greater chance for pathogen transmission to occur (33).

2.1.3 *Ixodes ricinus* and Lyme borreliosis

The most abundant tick-borne disease in Europe is Lyme borreliosis (LB, also called 'Lyme disease'), and *I. ricinus* is the principal vector in the UK. The causative agent of LB is *Borrelia burgdorferi* sensu lato (s.l.), a bacteria complex composed of multiple pathogenic and non-pathogenic genospecies. The most common genospecies reported in the UK are *Borrelia afzelii*, *Borrelia garinii*, *Borrelia valaisiana* and *Borrelia burgdorferi* sensu stricto (s.s.) (55 to 61).

The maintenance of *B. burgdorferi* s.l. relies on competent reservoir hosts such as small and medium-sized mammals and birds that become infected following a blood-meal from an infected nymph and subsequently transmit it to larvae. Ungulates such as deer and cattle are considered incompetent reservoir hosts as they do not transmit *B. burgdorferi* s.l. to ticks as their immune system eliminates the bacteria, but they are able to host large numbers of ticks, act as a staging post for adult tick mating, and are a key food source for adult female ticks (62, 63).

Whilst the incidence of LB in England and Wales is considered low compared with many European countries, it has increased from 0.5 per 100,000 in 2001 to 2.77 per 100,000 in 2018 (64). The incidence of cases locally can be significantly higher than the national average. In southern England, a known hotspot for LB, incidence rates of 9.8 cases per 100,000 have been reported (65). Similarly in the Scottish Highlands, 44.1 cases per 100,000 population have been recorded (66). Only laboratory-confirmed cases are included in national figures, and as cases diagnosed on clinical features, such as the presence of erythema migrans (67) are not included in national rates, the incidence of LB in the UK may be significantly higher than reported in official figures (66, 68 to 70). Whilst LB incidence has increased in many countries including the UK in recent years (64, 71 to 73), it is almost impossible to determine how much of the increase is down to climate change alone as the increase is likely to be multifactorial, including increases in both deer and tick distribution, as well as improved awareness of ticks and LB symptoms in clinicians, improved diagnostic techniques and increased testing.

2.1.4 Impact of climate and other environmental factors on the ecology of LB transmission cycles

Similar to national incidence rates reported above, *Borrelia* prevalence in urban ticks is much lower in the UK compared to other European countries (74). *Borrelia* infection rates in ticks in England have been studied at national and local levels. Mean nymph infection prevalence for England and Wales is 4% but varies from 0 to 10% (75). A more local (higher spatial resolution) study over 5 years found that nymph infection prevalence can vary by 4% to 12% in the same localities over time (59). Differences in *Borrelia* incidence in *I. ricinus* are driven by several environmental factors, including habitat. Woodlands are favourable habitats for ticks due to the humid microclimate preventing desiccation when ticks are off-host, coupled with the density of potential hosts (76, 77). A study of nymph and adult *I. ricinus* collected from sites across the UK found that ticks from deciduous woodlands were approximately 21 times more likely to be infected with *B. burgdorferi* compared with ticks collected from moorlands (55). In addition, ticks from deciduous woodlands had higher infection levels than ticks collected from conifer plantations and grasslands (55, 57).

An investigation into *Borrelia* spp. infection rates in nymphs in 5 different habitats across parts of southern Wiltshire during 2013 to 2017 found that infected nymph density was highest in woodland edge and high biodiverse woodlands (defined as varied canopy and understorey, with areas of hazel coppice and ancient woodland flora) compared to lower biodiverse woodland and open scrub habitats (59). There were no infected ticks in calcareous grassland sites during any of the study years (59), supporting other studies findings that grasslands without scrub habitat are generally unsuitable for ticks and have lower tick densities reported, despite woodlands being considered a source of ticks in adjacent habitat (78, 79). It is vital to consider that initiatives for biodiversity to increase woodland cover through planting trees, woodland regeneration and rewilding are likely to increase overall habitat availability for ticks and their hosts. Other management strategies such as woodland thinning, tree removal to prevent diseases such as Ash dieback, and improving public access can change the way a woodland is exploited by wildlife, change the microclimate for ticks and change the way people access the woodland, all of which can have implications for tick-borne disease transmission.

As well as being found in rural woodland habitats, *I. ricinus* populations have been observed in urban areas including woodlands, grassland and parks in cities in England (80 to 82). The expansion of urban areas into greenbelts, where new housing developments are constructed amongst existing or new tick habitats, can increase exposure to ticks and pathogens (80). It can also increase the interaction between tick hosts and humans through gardens (83), recreational areas, and school playing fields, which can have considerable implications for management and disease risk. Whilst the provision of increased urban greenspaces are important for improved health and wellbeing and to mitigate against warming cities and the urban heat island effect, they can provide additional habitats for ticks and provide wildlife corridors for tick hosts (84). As such, increasing connectivity between urban greenspace can drive tick survival and tick densities, which may be separate to, or indirectly affected by climate.

The genospecies of *Borrelia* infecting ticks can be affected by host presence and density. Many studies have identified *B. afzelii* as the predominant genospecies infecting ticks across Europe (82, 85 to 87), which is associated with small mammals. In England and Wales, *B. garinii* and *B. valaisiana* have been identified as the predominant genospecies (59, 75); and are associated with ground-foraging birds, including gamebirds. Due to the presence of the non-pathogenic species *B. valaisiana* in questing nymphs in England, it is possible that *B. valaisiana* may not be contributing to LB cases, so whilst prevalence rates in ticks may be high, it may not correspond to the incidence of LB cases.

Deer are widely considered key hosts of *I. ricinus*, with deer exclusions significantly reducing the density of questing ticks and ticks feeding on small mammals (88 to 92). In Scotland, low tick abundance was reported in areas with few deer but high nymph abundance occurred where abundance indices of roe and red deer were high (57, 89), yet no correlation with deer abundance and questing *I. ricinus* densities were found in the Netherlands (91). In Sweden, milder winters over a 30-year period with reduced snow cover and longer vegetation periods resulted in the increased survival and northerly expansion of both deer and *I. ricinus* populations (93). It has been suggested that warmer climate at high altitudes or latitudes could result in an increase in overall roe deer abundance through improved winter survival, earlier birth dates and increased plant growth to support deer populations (94).

2.1.5 *Ixodes ricinus* and TBEv

The UK has endemic transmission of the tick-borne arbovirus Louping ill virus (LIV), found mostly in upland areas of Scotland, England and Wales (95). Although LIV can cause issues for sheep and grouse, there has generally been little evidence of public health concern. Of greater public health concern is TBEv, the most common tick-borne arbovirus reported in Europe. Since the 1990s, the number of confirmed cases has increased by 400% (96). There are many factors explaining the rise in reported cases including TBEv becoming a notifiable disease in the EU in 2012. Whilst cases are reported from across Europe, the highest incidence rates are reported in the Baltic region (97).

The virus is a member of the Flavivirus genus (98), and to date, 3 subtypes have been confirmed (Western European subtype, TBEv-Eu; Far Eastern subtype, TBEv-FE; Siberian subtype, TBEv-Sib), with 2 additional subtypes recently proposed (Baikalian subtype, TBEv-Bkl; and Himalayan) (99, 100). The predominant route of transmission of TBEv is via the bite of a tick. Transmission can also occur following consumption of unpasteurised milk products from cows, goats and sheep infected with TBEv, although it is considered rare (101, 102). The predominant vector of the European strain is *I. ricinus*, whilst the Siberian and Far Eastern strains are mostly transmitted by *Ixodes persulcatus* (103).

Since 2019, there have been several detections of TBEv in the UK through ongoing surveillance of animals, ticks and humans. A large-scale surveillance study using serum and ticks collected from culled deer from across England and Scotland detected TBEv in 4% of serum samples, with 47.7% positivity rate from deer in Thetford Forest in the East of England (Figure 4) (15).

Five ticks from the Thetford Forest area also tested positive for TBEv (Figure 4) (15) and an estimated prevalence of 0.17% was reported in ticks collected near the Hampshire-Dorset border in southern England (104). Two probable cases of TBEv likely acquired in England were reported in 2019 and 2020. An infant tested positive for TBEv after being bitten by a tick acquired in the New Forest in southern England (105), and a male adult tested positive following a tick bite in Hampshire (106). Two probable cases were also reported in Scotland and Yorkshire during 2022.

Susceptible ticks (usually larvae) become infected with TBEv when they feed adjacent to an infected tick (usually nymphs) on the same host. This is known as co-feeding (also called non-systemic transmission) and does not involve virus amplification within the host (107).

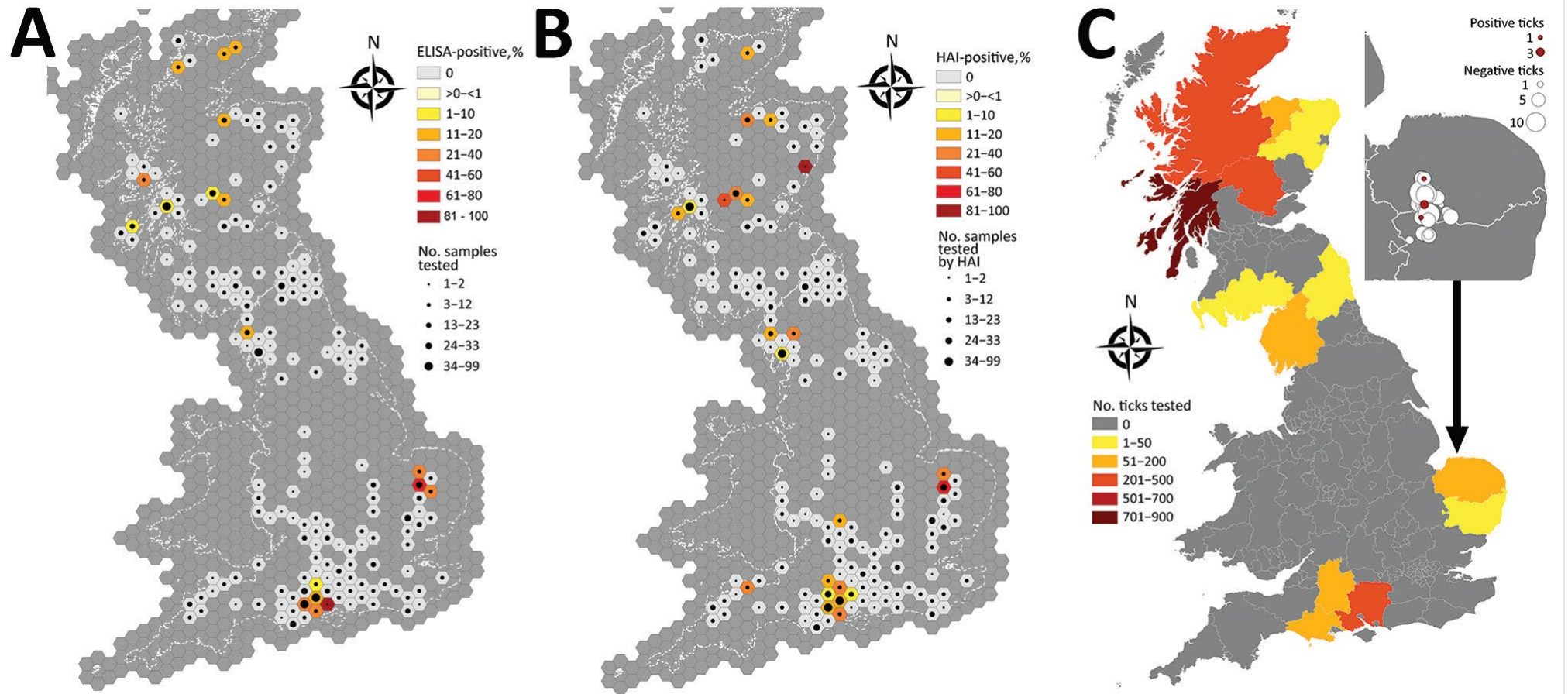
Small mammals are key hosts for the transmission of TBEv, and it is primarily associated with habitats such as woodlands that support large numbers of hosts. Transmission of the virus can also take place via ticks feeding on viraemic animals, or occasionally transovarially, with the virus passing from infected females to the eggs (98). Once infected, the virus persists within the tick and is transmitted transstadially (meaning from one life stage to the next), resulting in the infection lasting throughout the lifespan of the tick.

Weather conditions, particularly temperature, are important variables affecting the transmission cycle of TBEv. A study analysing conditions in sites within European TBEv foci compared with non-TBEv foci found that larvae were active and feeding on small mammals earlier in the year in TBEv foci: they appeared in the spring when nymphs were also active, increasing the likelihood of co-feeding occurring (108). In addition, sites within the TBEv foci were characterised by high rates of cooling in land surface temperatures during August to October relative to peak summer temperatures, leaving unfed larvae to overwinter and emerge alongside nymphs the following spring (108).

As discussed for LB, changes to the climate can impact tick activity, which will have consequences on transmission of TBEv. In 1994, a 3-fold increase in the TBEv incidence in Sweden was preceded by 5 very mild winters and the early arrival of spring for 7 consecutive years (109). Similarly, 4 cases of TBEv were reported in late February 2007 in Germany following an incredibly mild winter (approximately 4.6°C warmer than the long-term mean) when questing *I. ricinus* were detected throughout the winter (54). In the Russian Arctic, increased TBEv incidence has been correlated to warmer temperatures extending the period of the year when ticks (*Ixodes persulcatus*) are active (110). In Slovakia during the period 1961 to 2004, rising temperatures are hypothesised to have increased TBEv cases found at higher altitudes (111). A study investigating the potential impact of climate change on TBEv transmission risk in Hungary using climate projection data predicted that the density of questing ticks would increase in future, as well as result in a longer questing season, a longer period of the year when co-feeding between larvae and nymphs may occur, and increased chance of co-feeding transmission occurring compared with 1961 to 1990 (112).

Figure 4. Results for deer serum samples and ticks tested for tick-borne encephalitis virus (TBEv), United Kingdom

Number of samples tested and seroprevalence of samples positive by ELISA (A) and HAI (B), with numbers of ticks tested for TBEv by county (C), with inset showing magnification of ticks positive by real-time reverse transcription PCR (15).



As well as directly impacting tick ecology, climate conditions can affect host abundance and distribution, resulting in indirect impacts on TBEv transmission. A study of TBEv circulation in a foci in northern Italy found that a rapid decrease in late summer temperatures was associated with increased numbers of co-feeding tick on yellow-necked mice the following year, with co-feeding occurrence positively affected by roe deer abundance as well as co-feeding ticks positively affecting TBEv antibody detection in yellow-necked mice the following year (113). Similarly, common vole (*Microtus arvalis*) density with a lag of one year coupled with the inclusion of the annual North Atlantic oscillation (NAO) index with a lag of one year was the best predictor for TBEv incidence in Czechia, Germany and Slovenia (114).

Some studies have reported that non-climate factors have a significant impact upon TBEv incidence (115 to 118). For instance, in the Baltics during the period 1970 to 2006, an increase in both temperature and TBEv incidence was reported, yet the higher incidence was linked to socio-economic factors rather than the climate. The temperature increases occurred at the same time as the end of Soviet rule, which led to changes in land use and potentially exposed more people to ticks than previously (119, 120). The greater importance of host abundance and habitat type has also been highlighted by some studies (117, 118). Whilst deer are tick amplifying hosts, they can divert tick bites from competent hosts above certain high-density thresholds, and thus inhibit pathogen transmission (known as 'zooprophylaxis') (121). As a consequence of variation in deer abundance across regions, there are contrasting correlations between deer and TBEv incidence reported. For instance, the number of roe deer killed by hunters was negatively correlated with TBEv incidence in Finland and Italy (115, 122), yet positive correlations between roe and red deer abundance and human TBEv incidence have been reported in Sweden (116, 123) whilst there was no association between culled roe deer and TBEv in Czechia (124).

2.2 Native UK ticks: *Dermacentor reticulatus*

Dermacentor reticulatus, known as the ornate dog, ornate cow, meadow or marsh tick, is a 3-host tick, where immature stages feed on small mammals and adults feed on larger mammals such as dogs, deer, livestock (sheep, cattle) and occasionally bite humans. It is one of the most widely distributed tick species in Europe, found as far west as Portugal, and as far east as Ukraine and Turkey. The southern limit of *D. reticulatus* is in northern regions of Portugal, Spain and Italy, and the northern limit reaches parts of Wales and Latvia (125 to 128). In the UK, the distribution of *D. reticulatus* is localised to parts of West Wales, Devon, and Essex (126). Local expansions in distributions of *D. reticulatus* have been reported in several European countries including the UK (126, 129 to 131), and such expansions have been attributed to climate change as well as land use changes, travel patterns of humans and animals, as well as an increase in host availability (125). Changes in the distribution of *D. reticulatus* could have important medical and veterinary implications as it has been associated with the possible transmission of pathogens such as TBEv, *Rickettsia* spp., *Babesia* spp. and Omsk haemorrhagic fever (125, 132).

Temperature and humidity are known to affect the distribution *D. reticulatus*. It is found in moist environments with high humidity and wet soils, such as riverbanks, wooded or bushy river valleys, marshlands, swamps, grasslands and pastures, as well as in much drier areas such as sand dune habitats, maritime grasslands, and even urban parks (126, 133, 134). A study of 2,188 *D. reticulatus* records from Europe suggests that the presence is associated with warm temperate or boreal climates with year-round precipitation and warm summers (131). As it is more tolerant to cold weather than other tick species, *D. reticulatus* is active during the winter months, when temperatures may be too cold for abundant *I. ricinus* (135). As such, studies have reported active adults during late August and September until April and May, with the peak in adult activity occurring in March to May (128, 135). Larvae and nymphs are mostly active during July and August, although the immature stages are more nidicolous (remain in the nest) and are rarely detected during flagging or dragging surveys. A study conducting weekly sampling of active adult *D. reticulatus* from known locations in the UK found that adults were active during October and June, with the peak in activity occurring during February and March (136).

Weather conditions are known to directly affect *D. reticulatus* activity. Negative correlations between air temperature and questing ticks were reported in Poland and Czechia populations (137, 138), possibly driven by most ticks being collected during the autumn months (138). Tick activity was reduced when temperatures exceeded 20°C (139). In contrast, a positive relationship between adult activity and air temperature has been found in the UK, although questing activity was not observed when the 5-day mean temperature exceeded 15°C (136). Relative humidity affected *D. reticulatus* activity in northern Italy, with almost 82% of ticks collected when the 30-day mean relative humidity was under 70% (127). In Poland, the greatest number of ticks were collected when relative humidity was between 60% and 70%, and a decrease was seen when humidity levels were below 50% (139). In addition, the greatest levels of adult activity in a park in eastern Poland were seen when at humidity levels of 55% to 65% (140). In contrast, other studies have reported no significant effect of relative humidity on activity of *D. reticulatus* populations in Poland and Czechia (137, 138, 141). In addition, several studies have reported a negative correlation between saturation deficit and tick activity (127, 136, 139), highlighting the importance of water availability on questing activity.

From a public health perspective, there is little evidence so far that there is much human biting by *D. reticulatus* (20). From a pathogen perspective, *D. reticulatus* was implicated in the transmission of canine babesiosis in Essex in 2015 to 2016 (142), but there is no evidence that *Babesia canis* causes human disease. Infection of *D. reticulatus* in the UK with *Rickettsia raoultii* and *Rickettsia helvetica* has been reported (143, 144) although neither have been linked to human disease in the UK so far, and there is little evidence of significant human risk in Europe. Given its limited (albeit expanding) distribution, the scarcity of human biting reports, and limited evidence of pathogen transmission, there is lower public health concern for *D. reticulatus* compared with *I. ricinus*. However, ongoing surveillance of new and existing foci, host associations and pathogen detection will be prudent in a changing climate.

2.3 Native UK ticks: *Haemaphysalis punctata*

Haemaphysalis punctata, also known as the red sheep tick, is known to feed on sheep, cows, goats, as well as rabbits, horses, deer and is also known to bite humans. It is found in the Mediterranean (145) as well as in more temperate regions in northern Europe such as the Netherlands, Swedish islands in the Baltic Seas and parts of the UK (146 to 148). Unlike *I. ricinus*, *H. punctata* can survive in dry, hot conditions afforded by sheep pastures and calcareous grassland. In the UK the distribution is limited to parts of South-East England but is expanding, likely driven by movement of tick-infested livestock hosts and land management practices (147). In England, it has been implicated in tick pyaemia and abortions in sheep (149), and infection with *Borrelia miyamotoi* has been reported in a small number of individuals (150). To date there have been no studies investigating the effect of weather or climate change on *H. punctata* in Europe.

2.4 Non-native ticks of importance in the UK: *Hyalomma marginatum*

Hyalomma marginatum is found in southern Europe, North Africa, India, Iran and Pakistan (151, 152). It is the most important vector in Europe of Crimean-Congo haemorrhagic fever virus (CCHFV) (153), with cases reported from several countries across Africa, Asia, southeast Europe and the Middle East (154). *Hyalomma marginatum* is a ditropic (2-host) tick: engorged larvae usually remain on the host to feed as nymphs, engorged nymphs moult off-host and find a new host to feed on as adults (155, 156). Larvae and nymphs feed primarily on small mammals, hares and birds, whilst adults commonly feed on ungulates including cattle, sheep, horses, goats and camels (157). As adults feed on horses, movement of horses between countries could result in importation of *Hy. marginatum*, as has been previously reported (158). Migratory birds are important hosts of the immature stages, transporting them over long distances into novel areas during spring migrations. Given the potential for dispersal of immature *Hy. marginatum* by migratory birds, there is the possibility that in a changing climate, local populations will be able to establish outside of the current geographic range, as seen in southern France (159).

The main distribution area of *Hy. marginatum* are areas where annual cumulative temperatures are around an optimum of 3,000°C to 4,000°C and water vapour deficit is below 15 hPa (160). Areas north of this optimum temperature zone (north of parallel 47°N) are considered too cold for nymphal moulting to occur, resulting in 100% mortality rates, whilst in regions south of the zone (equivalent to 33°N), nymphs are subjected to high mortality rates due to water stress whilst moulting and questing as adults (160). Warm temperatures during autumn can lead to nymph populations moulting to adults, which will decrease mortality during winter as adult populations are more resistant to the cold than nymphs (24). Late autumn temperatures can significantly impact nymphal populations because there will be high mortality rates if nymphs fail to moult before cold temperatures commence (160). Air temperatures between 1 September

and 31 December are crucial for establishment of *Hy. marginatum*. Areas where there are established populations of *Hy. marginatum* experience average cumulative temperatures (temperature on day 1 plus temperature on day 2, and so on) of 800°C during September and December, whilst regions where the mean cumulative temperatures are below 400°C do not have established populations (24).

Whilst there have been historic detections of *Hy. marginatum* in the UK (161), since 2009 there have been 3 further reports. First, a male *Hy. marginatum* was recorded on a horse in Devon that had been imported from Portugal (158). Second, 14 *Hy. marginatum* nymphs were removed from 4 species of migratory birds captured during the 2010 and 2011 spring migrations in southern England (162). Finally, in June 2018, a male *Hy. marginatum* was found crawling on a person with no history of travel in the East of England (6). It was hypothesised that high temperatures in the lead up to June 2018 were sufficient for nymphal *Hy. marginatum* introduced via migratory birds to moult to adults (6). In addition to the detection in England, there were several reports of *Hy. marginatum* detections outside of its native range during summer 2018 in Sweden, Austria and Germany (163 to 165). It is thought that extreme hot and dry conditions during the summer of 2018 favoured the moulting of nymphs imported on migratory birds into adults (6, 163, 164).

2.4.1 Predicting the current and future risk of *Hyalomma marginatum* overwintering in the UK

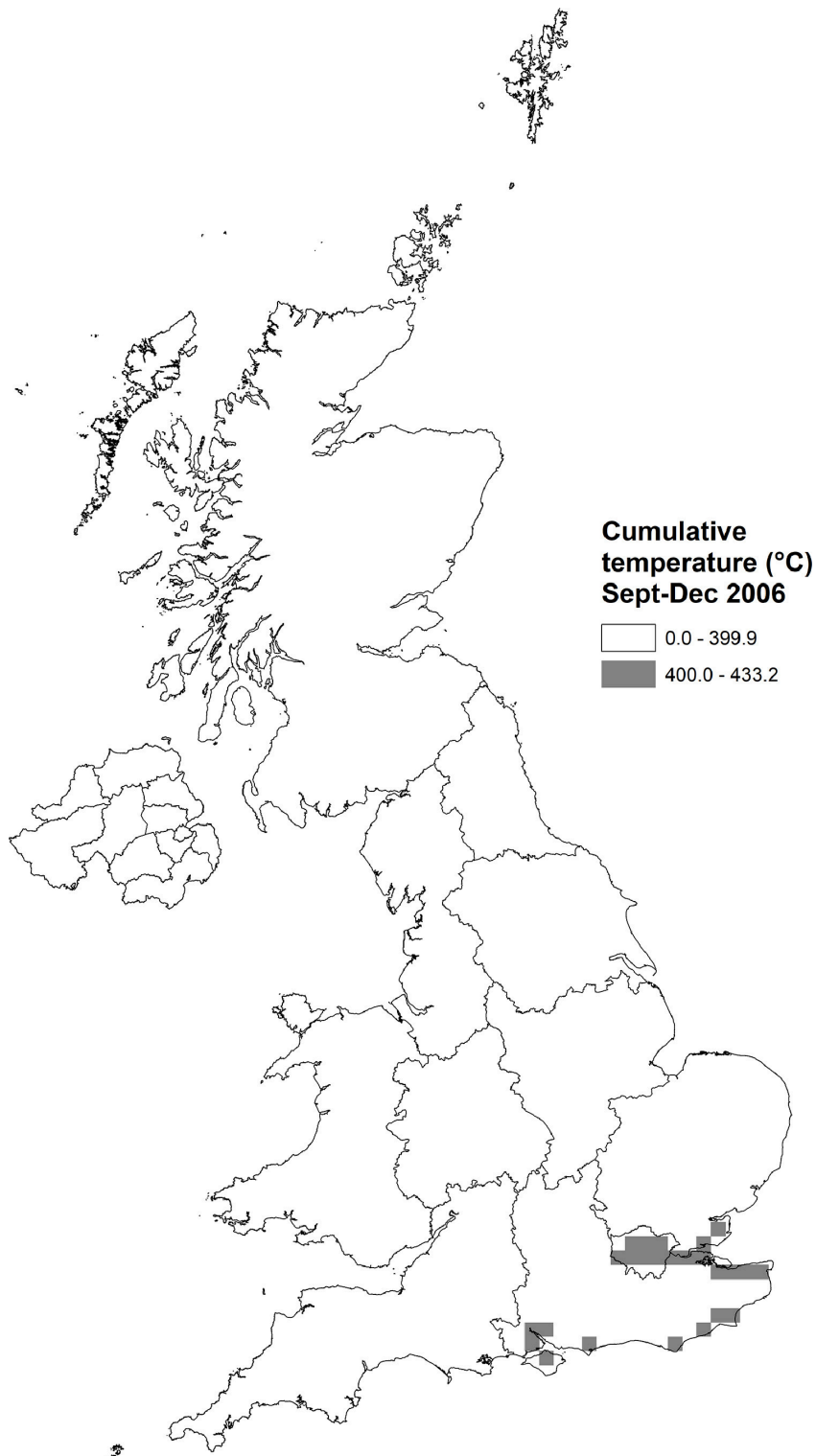
Temperature is the major parameter affecting seasonal patterns of *Hy. marginatum* (160). As temperatures between 1 September and 31 December are crucial for establishment of *Hy. marginatum* (24), a study was conducted to establish whether overwintering temperatures between 1 September and 31 December 2000 to 2019 were sufficient for survival of adult ticks, or whether projected temperatures would be sufficient in the future (166). Using a threshold of 10°C (following (167)), cumulative temperatures between 1 September and 31 December of each year during the period 2000 to 2019 were calculated for each 12km grid of the UK. In addition, cumulative temperatures for each year from 2021 to 2079 were calculated by summing the daily mean temperatures above a threshold of 10°C for each of the 12 sets of predicted daily temperatures from UKCP18 RCP8.5 data. The RCP8.5 data represents a high emissions pathway and should thus be considered a worst-case scenario, excluding mitigation and adaptation. Other RCP data was available, but at lower temporal (monthly rather than daily) and spatial (60km rather than 12km) resolutions and was unsuitable for the analyses. Due to the variation between the different model runs, cumulative temperatures from each of the 12 projections were averaged to produce a mean prediction per decade (2021 to 2030; 2031 to 2040; 2041 to 2050; 2051 to 2060; 2061 to 2070; 2071 to 2079).

Between the period 2000 to 2019, there was only one year (2006) where cumulative temperatures during 1 September and 31 December exceeded 400°C but did not reach 800°C (166). During 2006, there were 25 grids where cumulative temperatures exceeded 400°C (range: 400.4°C to 433.2°C) and these were all located in London and along the south-eastern coast of England (Figure 5). The mean temperature during September 2006 (15.20°C ± 0.03)

was higher than during September in any other year, but there was no difference in temperatures during October, November and December 2006 compared to any other year.

Figure 5. Cumulative temperatures above a 10°C threshold between September and December 2006

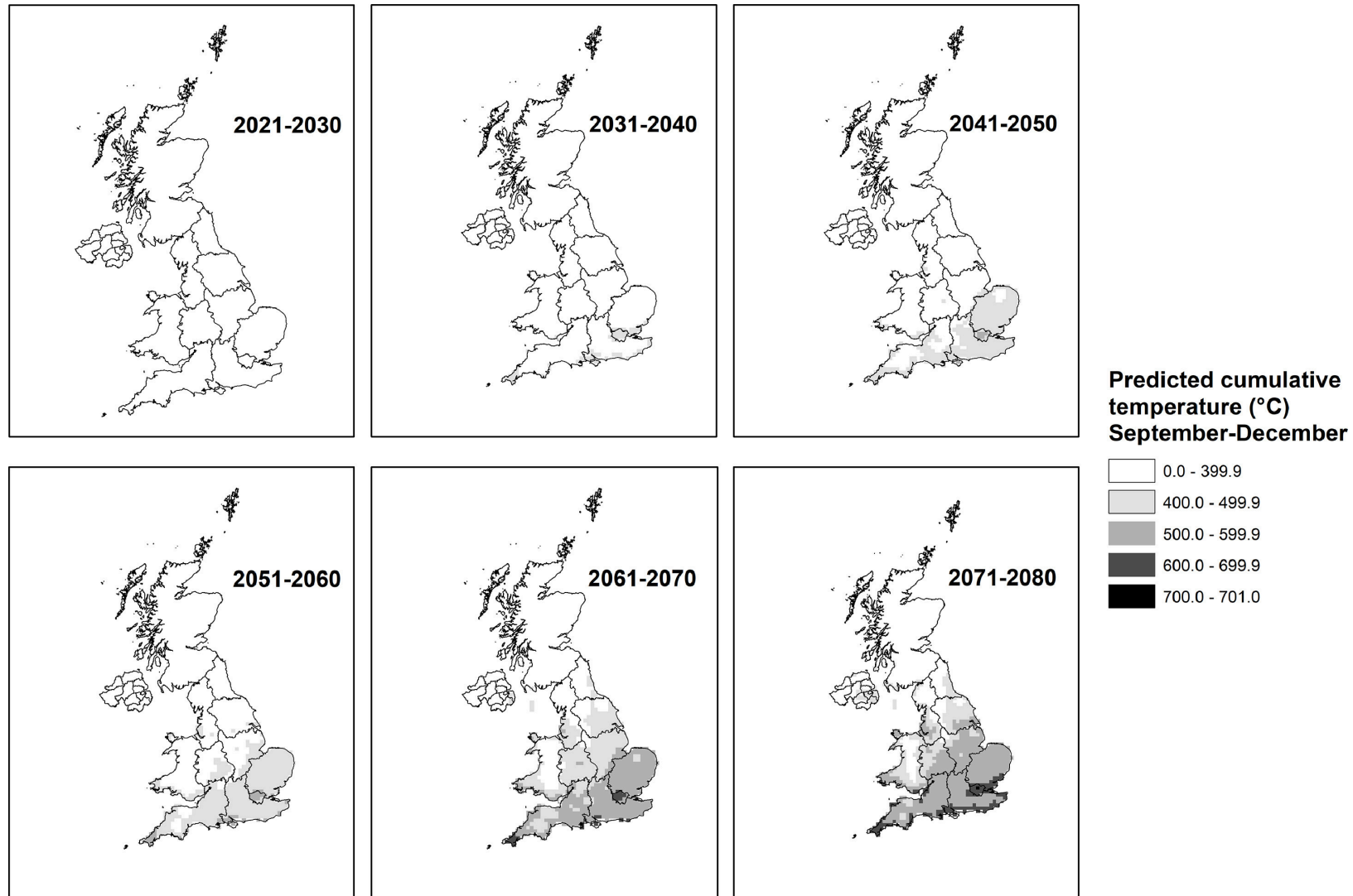
Grids that exceeded 400°C are shown in grey, areas with a mean below this are considered unsuitable for establishment of *Hy. marginatum* ([166](#)).



When considering future UK temperatures using UKCP18 projections, calculations predicted that between 2021 to 2079 there could be an increase in the number of years where cumulative September to December temperatures will exceed 400°C (Figure 6). From 2030s onwards, cumulative temperatures were predicted to exceed 400°C, and exceed 700°C by the 2070s (Figure 6). Across the study period, the highest cumulative temperatures were predicted for London and coastal parts of southeast and southwest England (Figure 6). Whilst on average cumulative temperatures did not exceed 800°C, there were variations between model runs, with 800°C exceeded during some model runs (166). These findings suggest that autumn temperatures in the UK currently are too low for moulting from nymphs to adults to occur and likely result in high mortality. In addition, whilst autumn temperatures will be warmer in future, the threshold required for establishment of *Hy. marginatum* populations in the UK was not met, even using the worst-case scenario data (166).

Figure 6. Mean predicted cumulative temperatures above a 10°C threshold between September and December, averaged per decade, based on the UKCP18 RCP8.5 projections for the UK

RCP8.5 (considered a worst-case scenario) projections were used as other RCP data was not suitable for the analysis ([166](#)).



2.5 Non-native ticks of importance in the UK: *Rhipicephalus sanguineus*

Rhipicephalus sanguineus s.l. is a species complex comprised of 12 tick species: *R. sanguineus* s. s., *R. sulcatus*, *R. rossicus*, *R. schulzei*, *R. pumilio*, *R. pusillus*, *R. turanicus*, *R. leporis*, *R. guilhoni*, *R. moucheti*, *R. bergeoni* and *R. camicasi* (168 to 170). Known commonly as the brown dog tick, as the name suggests, *R. sanguineus* primarily infests dogs, although incidental biting of humans has been described (171, 172). Unlike common tick species in the UK *R. sanguineus* can survive inside buildings, including residential homes. Despite *R. sanguineus* being more commonly associated with the Mediterranean areas in Europe, it is capable of surviving in temperate regions, where it is active between spring and autumn (173). Even though *R. sanguineus* is not native in the UK, there have been instances when it has been associated with travellers recently returned from abroad (4, 5) or with dogs with recent travel history (10, 11, 174).

There is evidence that warmer temperatures increase aggressiveness of *R. sanguineus* to humans, resulting in increased biting rates (175), with attachment and feeding occurring more rapidly under warmer temperatures on unusual hosts (176). Laboratory experiments suggest that *R. sanguineus* adults are more likely to bite humans under high temperature (38°C) compared with room temperature (23.5°C), and under the high temperature, there was a slight increase in preference to biting humans compared with dogs, suggesting that biting and thus diseases transmission to humans may increase during hot weather events (177). In addition, an increase in mean temperatures of 2°C to 3°C during the period April to September could result in distribution changes of *R. sanguineus*, resulting in established permanent populations in regions of northern Europe where it is currently absent (24).

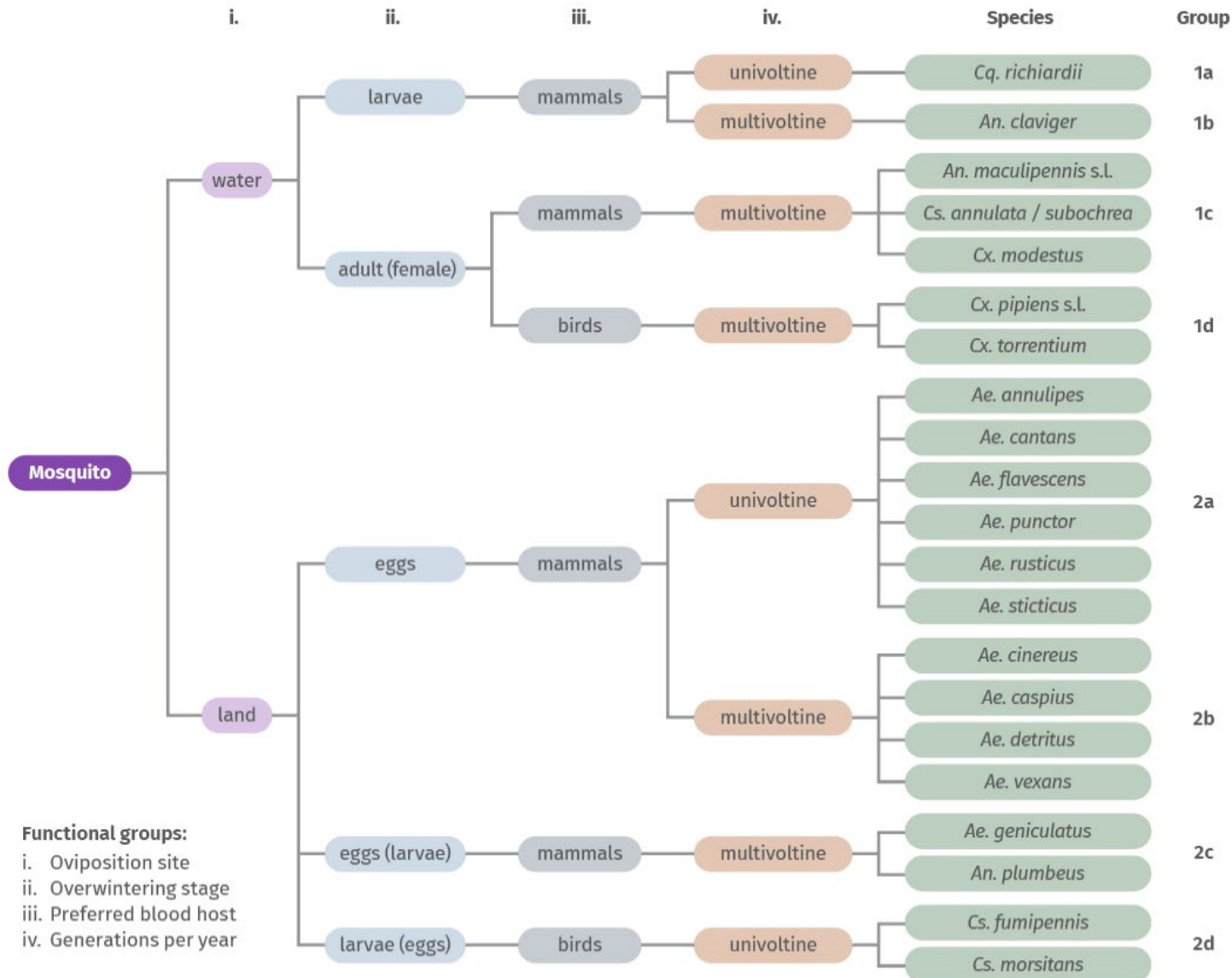
3. Mosquitoes and mosquito-borne diseases

3.1 Native mosquitoes in the UK

The UK currently has 36 recorded species of mosquito ([18](#), [178](#), [179](#)) with approximately 20 species considered common ([180](#)); however, some species such as *Aedes albopictus*, are not yet considered established. There are 6 species of anopheline and 30 species of culicine mosquitoes, which include several genera: *Aedes*, *Culex*, *Culiseta*, *Coquillettidia* and *Orthopodomyia* (Figure 7). Recent papers ([181](#), [182](#)) and the 'Wetland Mosquito Survey Handbook' ([179](#)) have ordered the common British mosquitoes into functional groups (Figure 7) and this has now become a standard for considering the British fauna and is a useful tool when considering the impacts of weather, climate and wetland management. Some functional groups respond to flooded habitats, whilst others respond to more permanent aquatic habitats. Being able to group the species by functional groups enables a better assessment of the impact of climate and weather events.

Figure 7 (below) categorises British mosquitoes into functional groups based on life history traits including where they lay their eggs, overwintering life stages, preferred blood host and the number of generations produced per year. Categorising the many species of mosquito into groups with similar life histories can enable a better understanding of the mosquito family. Functional groups give an overview of relatedness between different mosquito species according to their behaviour, seasonality and life history traits (rather than their taxonomic closeness).

Figure 7. Functional groups of British mosquitoes, where Ae = *Aedes*; An = *Anopheles*; Cx = *Culex*; Cs = *Culiseta*; Cq = *Coquilleltidia*; Or = *Orthopodomyia* (179)



Many species of these genera have ubiquitous distributions in the UK, for example, *Culex pipiens* typical biotype is a common house mosquito found breeding in a range of container, nutrient-rich and flooded habitats in urban and rural areas. During autumn, it seeks shelter to overwinter and is often noticed coming into people's homes. The typical form is ornithophilic, whereby it rarely bites humans, preferring to feed on birds, whilst the rarer autogenous mammalophilic *molestus* form is known from only a few subterranean urban locations. *Culex pipiens* s.l. can be an important enzootic vector of viruses and is a proven vector of pathogens to birds (for example, avian malaria, Usutu virus) ([179](#)). Many of the other UK *Culex* species tend to only bite birds, except the relatively recently discovered *Culex modestus*, a principal vector of West Nile virus (WNV), which bites birds and mammals ([183](#)). The *Aedes* mosquitoes include several subgenera: *Aedes*, *Aedimorphus*, *Ochlerotatus* and *Finlaya*, with the recent addition of imported detections of members of the subgenus *Stegomyia* (for example, *Aedes albopictus*) ([18](#)), although this latter species is yet to establish. These species tend to adopt a strategy of laying drought-resistant eggs in areas subjected to subsequent flooding, such as in wet woodland, summer flooded grassland, tree holes and, in the case of *Stegomyia*, in container habitats. This means that these species are highly responsive to natural and anthropogenic flooding and water capture systems ([184](#), [185](#)). Coastal flooding, riverine flooding, or storage of rainwater during drought or after rains, can all provide habitats for the *Aedes* mosquitoes to exploit, often to high densities, and often causing nuisance biting. *Aedes detritus* (and sometimes *Aedes caspius*) can be problematic in coastal areas associated with tidal and estuarine flooding, *Aedes cantans*, *Aedes annulipes* and *Aedes sticticus* can cause nuisance biting near wet woodlands, and *Aedes vexans*, although not currently common, can cause major nuisance issues along summer flooded river valleys ([185](#)).

Whilst other genera tend to play more minor roles as nuisance species or in disease transmission, *Culiseta annulata* can be a nuisance species early and late in the year. *Coquillettidia richiardii* can cause biting and is a potential arbovirus species but does not generally cause nuisance in the UK ([186](#)).

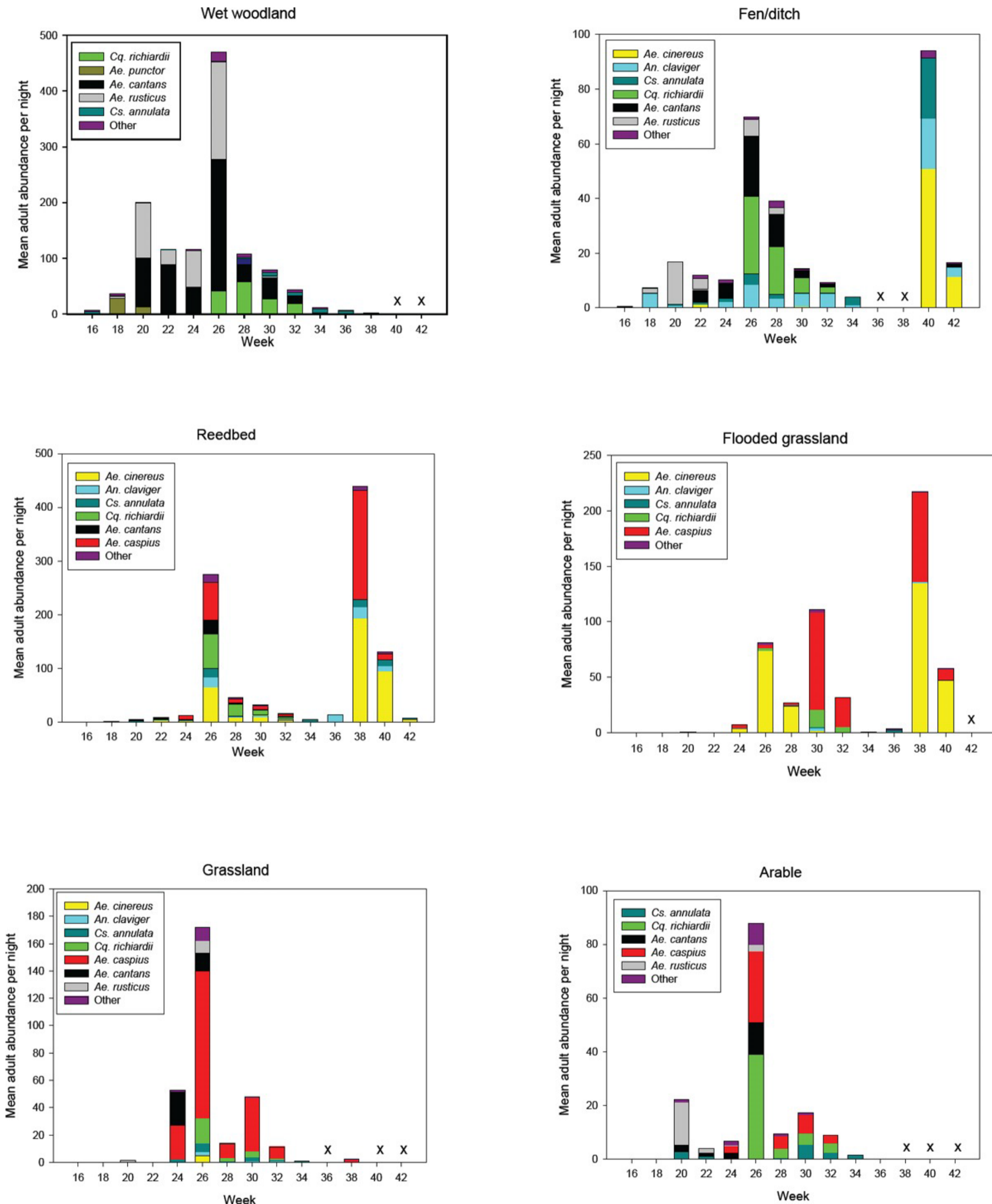
The primary species of concern for disease transmission currently and in a changing climate, include *Culex modestus* and *Culex pipiens* and their potential for transmission of WNV ([180](#)), *Culex pipiens* and transmission of Usutu virus ([187](#)), *Aedes albopictus* for the potential to establish in the UK, and future role in possible transmission of dengue, chikungunya and Zika viruses ([18](#)), the *Anopheles* species as potential vectors of *Plasmodium malariae* in the UK ([188](#)) and *Aedes vexans* as a possible vector of Rift Valley fever virus, and other arboviruses such as Tahyna virus ([189](#)). Focus will therefore be given to these species.

3.1.1 Effect of wetlands on native mosquitoes

The fenland habitats of Cambridgeshire at Woodwalton Fen typify UK mosquito diversity. The mosquito species diversity and abundance were studied to compare how 6 specific wetland types (wet woodland, fen and ditch habitat, reedbed, flooded grassland, grassland and pasture or arable farmland), all typical of lowland UK wetland habitats, contributed to varying diversity of mosquito species ([182](#)). This work highlighted the variability and focal nature of mosquito

species diversity and abundance, as all these traps were placed in different parts of the same wetland system, at various stages from open grassland, through various (permanently and transiently flooded) wet habitats through to wet woodland.

Figure 8. Mean number of adult mosquitoes trapped during fortnightly 4-night surveys in 6 adjacent habitats (wet woodland, fen and ditch, reedbed, flooded grassland, grassland and arable) in a wetland system in Cambridgeshire. x indicates no trap data (182)



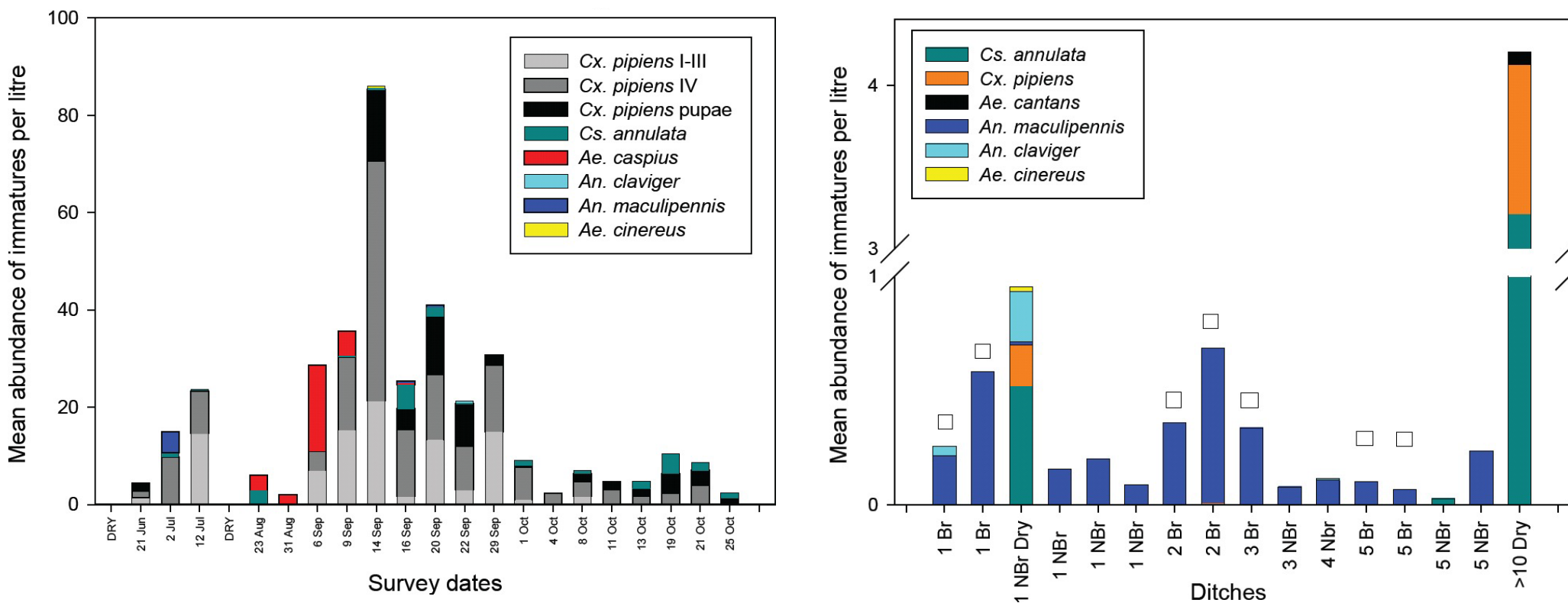
These species lay eggs in dry summer habitats subject to late summer rains, or human-directed flooding. All these species are notable nuisance biting species, and yet all are specifically responsive to extreme rainfall events, particularly after drought periods. The summer seasonality of the rest of the mosquitoes are dictated by temperatures.

In general, many of the remaining species in permanent water habitats tend to occur at lower densities, likely kept in control by a raft of predators. This controlling factor, along with the decreased variability in water levels, reduces the opportunity for boom-and-bust densities, witnessed by the floodwater mosquito species.

3.1.2 Impact of flooding and drought on British mosquitoes

Studies have investigated the impact of drought and flooding on 2 key habitats: flooded grassland and permanent water ditches ([182](#)). During the early part of the season in flooded grasslands, when wetland habitats are veering towards permanence, *Anopheles* mosquitoes were present, accompanied by low densities of the common *Cx. pipiens* s.l. (Figure 9a). Between mid-July and late August, the flooded grassland dried out as a result of drought. Within 2 weeks of the grassland re-wetting (due to abstraction from local watercourses, although similar to extreme rain event causing flooding) there was rapid hatching of mosquito eggs, following by larval development and emergence of large densities of *Ae. caspius* (Figure 9a). Following this, *Cx. pipiens* s.l. densities increased in a flooded habitat largely denuded of predators due to this flooding event. The rapid increase in first *Aedes*, then *Culex* mosquitoes illustrates the impact of drought and re-wetting on contributing to mosquito densities that could facilitate disease transmission. In the second figure (Figure 9b), immature mosquito densities across a season in 16 freshwater ditches are illustrated. Fourteen of these ditches remain wet all year and are dominated by low densities of *Anopheles maculipennis* s.l., but higher densities in those subjected to vegetation management, thus increasing sunlight and water temperatures. The remaining 2 ditches, both of which dried out during the 2010 drought and then re-wetted, lost their *An. maculipennis* s.l. populations, to be replaced by opportunist species, such as *Cx. pipiens* s.l. and *Cs. annulata*. Drought (and subsequent re-wetting) can therefore change the mosquito species assemblage dramatically, this further contributing to enzootic disease transmission risk ([182](#)).

Figure 9. (a) abundance of immature mosquitoes in a flooded grassland, before and after a period of drought, depicting the initial emergence of floodwater *Aedes* mosquitoes, followed by *Culex pipiens* colonisation and (b) impact of the same drought period, and vegetation management on 16 ditches habitats, depicting the preference of *Anopheles claviger* and *Cx. pipiens* in drought-affected ditches, and preference of *Anopheles maculipennis* in permanently wet ditches with managed marginal vegetation (182)



More recent research on British mosquito seasonality and habitat specificity has been conducted as part of the NERC Wetland Life project (179) which aimed to first develop a mosquito prediction tool for wetland managers to attribute wetland specificity to mosquito species, and to then test the tool in the field through field surveillance data. This takes forward previous work on wetlands and mosquitoes in the fens (182), other work on mosquitoes in coastal habitats (190), urban wetlands (191) and a previous synthesis of this topic (181).

Recent mosquito field work (Medlock, in preparation) informing the 'Wetland Mosquito Survey Handbook' (179) further enforces this result that mosquito densities in the UK are driven by flooded habitat species. Combining data from 12 wetland sites over 2 years (2017 to 2018) across England, high densities in spring are largely related to high densities of woodland *Aedes* mosquito species, primarily *Ae. cantans/annulipes*. During the summer months, species such as *Cq. richiardii* and *Anopheles claviger* are the most common with the former associated with permanent ditch and reedbed habitat, and the latter also found in flooded habitats. From mid- to late-summer, specialist open habitat floodwater species, such as *Ae. caspius* can reach high densities, but their distribution tends to be focal, and only reach high abundance in a few locations, using coastal sites subject to estuarine flooding. In early autumn, coastal species, such as *Ae. detritus* are abundant, consistent with the nuisance biting previously reported (186, 192). Translating this species-specific data into functional groups there is a predominance of 2 key functional groups (2a, 2b) associated with flooded habitats.

There are other species that have very focal distributions and are not generally captured in great numbers by widespread mosquito surveillance and monitoring, but where they do occur can cause intolerable levels of nuisance biting. The detection and subsequent biting associated with *Ae. vexans* in the valley of the river Yare, on the southern edge of Norwich in 2017 has been previously reported (193). This species had previously only been reported as occasional records, and this constituted the first viable population in the UK for 90 years, with population densities remaining low. In 2017, reports of persistent nuisance biting were reported from a village in rural Nottinghamshire, close to the valley of the river Idle. *Aedes vexans* was detected in mosquito trapping, and subsequent field studies found huge numbers of larvae in the flooded meadows either side of the river. At the peak in abundance, adult numbers in a single trap exceeded 19,000 over 4 nights (189). Extreme rainfall events and river flooding was implicated in the emergence of large numbers of nuisance *Ae. vexans* mosquitoes, accompanied by a range of other floodwater species (Vaux, in preparation). After each river flooding event during the summer months, densities of *Ae. vexans* larvae increase, thus illustrating that river systems prone to summer flooding after each significant rainfall event can lead to extremely high densities of floodwater nuisance mosquito species.

Aedes vexans is a polycyclic (many generations) mosquito species breeding predominantly in inundated areas such as floodplains of rivers and lakes with fluctuating water levels. In temporary flooded wet meadow and swamp habitats in continental Europe, large populations can develop, causing significant nuisance biting (185). Larval development can be rapid in temporary water bodies that remain wet from just a few days to several weeks, such as flooded meadows, and low-lying areas with willow and reed (185). Each female mosquito can lay 100 eggs and take multiple bloodmeals. Eggs can hatch shortly after flooding if the water temperature exceeds 9°C, with larval development as rapid as 1 week at 30°C and up to 3 weeks at 15°C (185). Eggs can survive for up to 5 years if flooding does not occur after oviposition, with eggs normally in diapause during colder months (September to March) (185). Upon flooding, eggs hatch in response to oxygen depletion: eggs do not hatch synchronously, but instalment hatching occurs to maximise survival should aquatic habitats dry out before adult emergence (185). Where conditions support development, huge numbers of larvae can be

found, with hundreds per litre and more than 100 million per hectare ([185](#)). This mass emergence creates pressure for seeking blood meals and females may be forced to migrate up to 15km from their breeding sites, with these founder sites leading to significant migration to other potential habitats ([185](#), [194](#)).

In some parts of Europe, particularly after flooding events, *Ae. vexans* can become an abundant nuisance species, often during the daytime, particularly along the river valleys of central Europe ([185](#)). Although known to prefer biting mammals, the species is known to be ornithophilic (bird-biting) as well ([195](#)). In the Upper Rhine Valley, *Ae. vexans* is the most abundant species found in riverine floodwater habitat, making up more than 90% of the populations during summer ([196](#)). In Europe, the mosquito has been implicated in the transmission of Tahyna virus (TAHV) ([197 to 199](#)) and further afield in Africa, it is a notable vector of Rift Valley fever virus ([200](#)). It is also considered a vector of *Dirofilaria* in Europe ([201](#), [202](#)). Whilst it is not involved in disease transmission in the UK to date, *Ae. vexans* is likely to present a biting nuisance locally.

3.1.3 Native mosquitoes and the threats posed by West Nile virus and Usutu virus

West Nile virus (WNV) is a flavivirus primarily transmitted in a cycle between *Culex pipiens* mosquitoes and birds ([203](#)) that can spill over to human and equine populations causing encephalitis and death in vulnerable groups ([204](#)). Several UK mosquito species have been identified as potential bridge vectors of WNV in the UK on account of their ability to bite birds and humans, and thus act as a link vector for transmission ([180](#)). Crucially, whilst the dominant enzootic vector *Cx. pipiens* typical form is ubiquitous in the UK, it rarely bites mammals (including humans), and therefore it was considered that transmission by *Cx. pipiens* may be limited to areas where *Cx. pipiens* biotype molestus occurs. Nuisance biting associated with the molestus biotype appears to be limited to certain parts of London, where it has adapted to sewage treatment systems and underground cloistered habitats. It is likely that this species occurs elsewhere in the UK, but biting is not common.

One of the principal vectors of WNV in continental Europe is *Cx. modestus*, which was only reported in the UK in the 1940s ([180](#)). However, during routine mosquito surveillance in 2010, significant populations of *Cx. modestus* were detected in the North Kent marshes, an area that had been widely surveyed for mosquitoes previously ([205](#)). Since 2010, the distribution of *Cx. modestus* in the UK has been monitored through annual surveys to study mosquito densities and monitor expansion to other parts of the region and more widely through nationwide surveillance. The Medical Entomology group in UKHSA (previously Public Health England) have run mosquito traps at more than 100 locations across England, with some sites in Northern Ireland coordinated by Agri-Food and Biosciences Institute Northern Ireland (AFBINI). During this time, traps have been run for over 16,500 trap nights and have collected more than 175,000 mosquitoes (Vaux, in preparation). From the surveillance, it is evident that *Cx. modestus* is known to occur across the North Kent marshes from Swanscombe in the west to Stodmarsh in the east, with notable populations on the Hoo peninsula and Isle of Sheppey. It also occurs on the Essex coast from Rainham in the east, in the marshes near Basildon and Colchester, up to

Horsey Island. Whilst so far there have been no records in Suffolk or Norfolk, it has also been reported in 2 locations in the Cambridgeshire fens although these are so far very focal or at low abundance.

3.1.4 West Nile virus potential establishment in the UK in current and future climates

As WNV continues to expand northwards in Europe, having recently been reported in both Germany and the Netherlands ([206 to 208](#)), there is growing concern that migratory birds travelling from endemic areas could introduce the virus to the UK ([209](#), [210](#)). However, questions remain around the current and future suitability of the UK climate for WNV establishment. Firstly, are projected temperatures high enough to sustain transmission cycles? If so, will pathogen introduction coincide with a period of sufficiently high vector activity? Is the vector biting season long enough to allow sufficient amplification of the pathogen in the vector and host populations to facilitate spillover into humans? Finally, how might likely shifts in the timing of these events affect outbreak risk under future climate scenarios?

To address these questions a novel mathematical modelling approach was developed ([211](#)) that explicitly models temperature effects on the timing and seasonal coincidence of events in the pathogen, host and vector life cycle (Figure 10). Predictions of the risk of WNV establishment in marginal temperate environments under climate change in the UK were made. Specifically, systems delay-differential equations (DDEs) with environmentally driven delays to incorporate realistic, climate-dependent representations of vector vital rates and pathogen latency were used, thus capturing the impacts of climate on seasonal variations in vector–host ratios on transmission risk. Furthermore, the method allows the capture of developmental lags in both vector population dynamics ([212](#), [213](#)) and the transition of exposed to infectious mosquitoes, facilitating understanding of whether the time between pathogen introduction and the cessation of the active vector season is sufficient to allow amplification of the pathogen to levels which may cause spillover into humans. Simulations of the WNV model were made using the UK Climate Projections 2018 (UKCP18) ([214](#)) under representative concentration pathway 8.5 (RCP8.5) as a high emissions ('worst-case') scenario at 12 km grid resolution. Risk maps showing minimum infection rate (MIR - the number of infectious mosquitoes per 1,000 adult females) for each grid square for each of the 12 sets of predicted temperature data were produced for the last year of each decade from 2019 until 2079. Under this model, the vector seasonal abundance patterns and pathogen replication rates will vary temporally across years and spatially across the UK because of differences in input temperature and photoperiod (the number of daylight hours per day). Three different WNV introduction times were considered: introduction at the end of March, the end of April and the end of May. These timings are consistent with the arrival times of a range of potentially competent migratory hosts such as the swallow, chiffchaff and willow warbler ([215](#)), among others ([209](#)).

The model predicts that, while current UK temperatures appear too low for WNV transmission cycles to be established, projected increases to UK temperatures in the coming years will increase the risks of WNV outbreaks, with epidemics possible by the second half of the century,

with South-East England the most at risk (211). The outbreak risk is predicted to increase as WNV introduction occurs later in the period from March to May and the risk remains highest in South-East England (Figure 11). However, the rate at which risk increases over time is strongly dependent on the relationship between WNV replication rates and temperature in the vector. The degree to which increased temperatures may increase the length of the mosquito biting season is also predicted to have a large impact on outbreak risk, with longer seasons leading to substantial increases in both the area at risk and the size of outbreaks (211). The model predicts that high biting rates and viral replication rates do not necessarily lead to high infection rates if the number of vectors per host is not also sufficiently high (211). The finding suggests that perhaps shorter periods of extreme warm weather, which are predicted to become more common in coming years (214), may not lead to substantially increased WNV risk if they only serve to increase biting rates and viral replication rates for a time. Rather, it may be cumulative effects of increased temperatures over whole seasons, perhaps coupled with longer periods of weeks or months of extreme temperatures, which lead to larger vector populations and consequently increased risk of VBD (211).

Figure 10. Schematic showing the relationships between the mosquito, bird and human populations, as defined in the model, and highlighting the processes by which individuals transition between infection classes, subject to the disease-related parameters (211)

Disease transmission processes are shown by dashed lines, while mosquito and bird life cycle processes are shown by solid lines. Transmission between the vector and host populations occurs through infectious mosquitoes feeding on susceptible birds and susceptible mosquitoes feeding on infectious birds. Disease transmission within the host population can also occur through host-to-host transmission and in the mosquito population through vertical transmission (from parent to offspring).

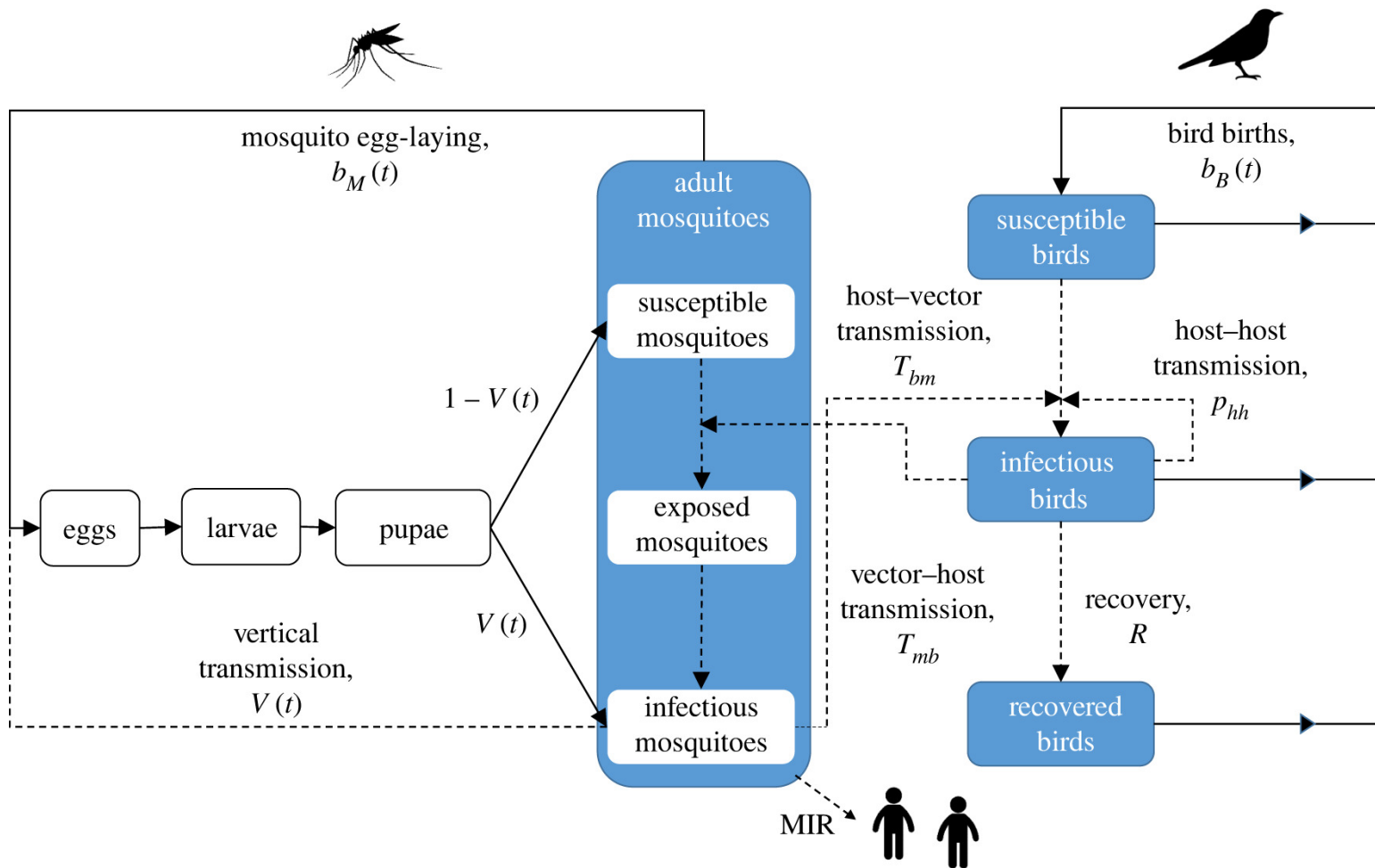
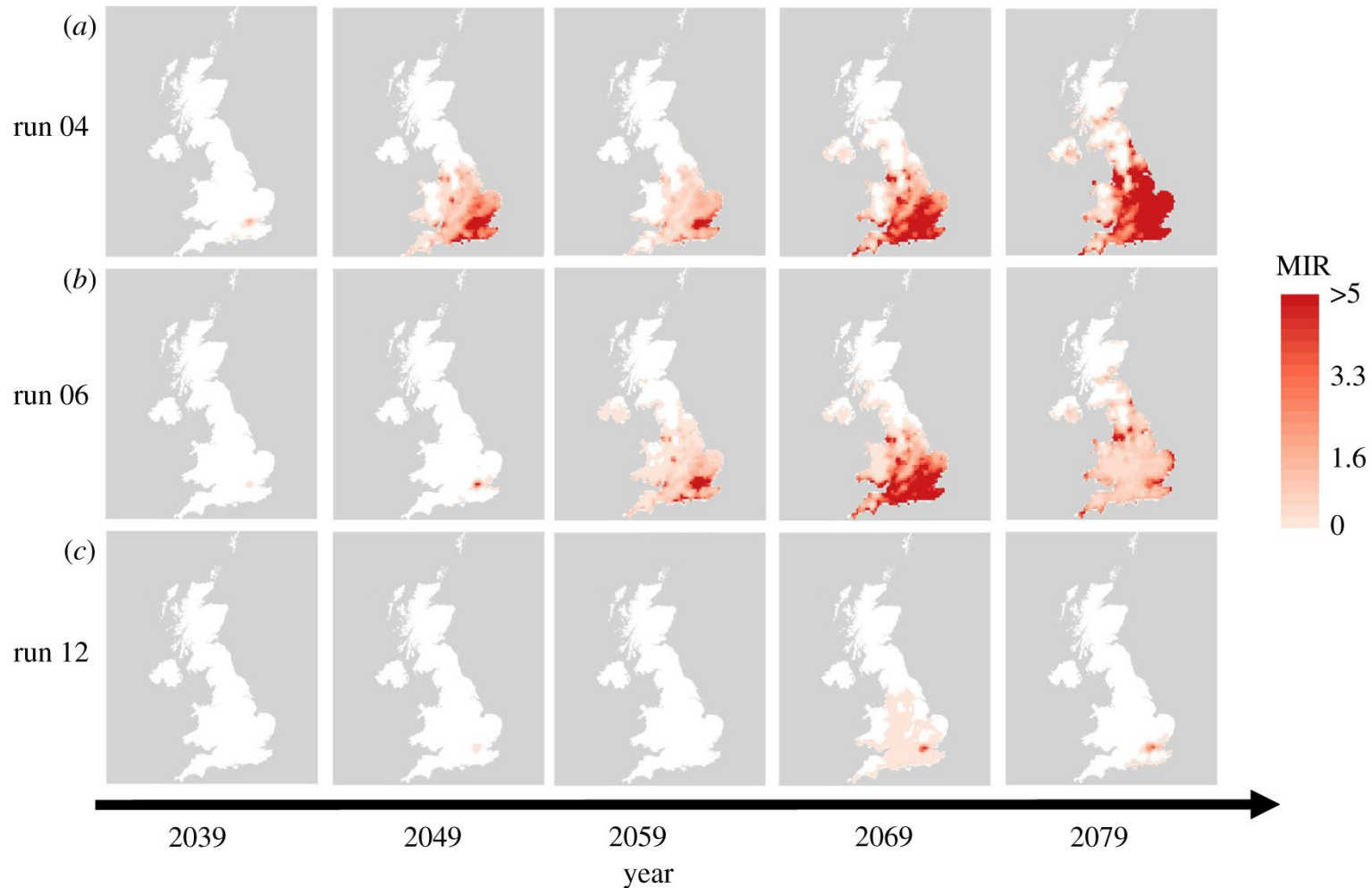


Figure 11. Upper limit of West Nile virus (WNV) risk given lower thermal minimum for WNV replication

The risk of WNV outbreaks (the minimum infection rate, MIR) via the arrival of migratory birds at the end of May for the temperatures simulated using UKCP18 model runs 04 (a), 06 (b) and 12 (c) are shown (211). The 5 columns correspond to results from 2039, 2049, 2059, 2069 and 2079 from left to right. In this case, the thermal minimum for WNV transmission has been set to the lower limit of the estimated 95% CI, which is 7.3°C (216). Due to very low estimated risk, only maps from 2039 onwards are shown (211).



3.2 Non-native mosquitoes in Europe and the UK

Over the last 30 years, several non-native mosquito species have been transported to Europe and subsequently established and spread. The most notable is the Asian tiger mosquito, *Ae. albopictus*, which can transmit several arboviruses including dengue fever, chikungunya and Zika virus (see below), and therefore presents a public health concern in areas where it could become established.

Aedes albopictus is native to Southeast Asia, but has become established in the Americas, parts of Africa, Australasia and parts of Europe. The first European record was reported in Albania in 1979, but it started to spread following importations into Italian ports in 1990. Since then, it has become widely established across Italy and has spread down the Adriatic, into Greece and Turkey, along the Mediterranean coast into France and Spain, and is now established in approximately 30 European countries (217). The initial route of importation was associated with the trade in used tyres and wet-footed plants, but now it is transported and disseminated by the movement of vehicles into the Netherlands and Germany. It has become widely established throughout France, with records in Brittany and established populations in Paris (217). It has developed mechanisms to withstand winter temperatures of temperate regions (218, 219), which has likely aided its expansion into northern Europe. Mosquito surveillance and associated control has been intensified throughout its range, and this has led to the discovery of other non-native mosquito species including *Aedes japonicus* and *Aedes koreicus*. *Aedes aegypti*, a more efficient vector of dengue, chikungunya and Zika viruses (ZIKV), was once established across Europe but subsequently disappeared; it has since returned to parts of southern Europe, with established populations in southern Russia, parts of Georgia and Turkey and Madeira (217).

In the UK, invasive mosquito surveillance at ports was instigated in 2010. Following the ZIKV outbreak in the Americas during 2016, port and highway surveillance was extended and currently between 40 and 60 trapping locations are maintained and coordinated through a collaboration between UKHSA and local and port health authorities (17, 220). Since 2016, cross-government action has taken place to develop and implement a contingency plan for the detection of invasive mosquitoes in England (221). At a baseline level, this involves a network of invasive mosquito trapping locations, coordinated by UKHSA and implemented by local authority teams. Any detections trigger a local public health incident, with strategies implemented for enhanced surveillance and rapid control measures including source reduction and biocides.

Eggs of *Ae. albopictus* were first detected in a motorway service station ovitrap in Kent in September 2016 (18). Over the following 3 years, further eggs and larvae were detected in other transport hubs in Kent and in an import distribution centre in West London (17). All incursions during 2016 to 2019 were detected in either late July or in mid-late September (17). On each occasion, the contingency plan (221) was triggered. There were no detections during the summers of 2020, 2021, 2022 or 2023. Invasive mosquito surveillance at sea and airports,

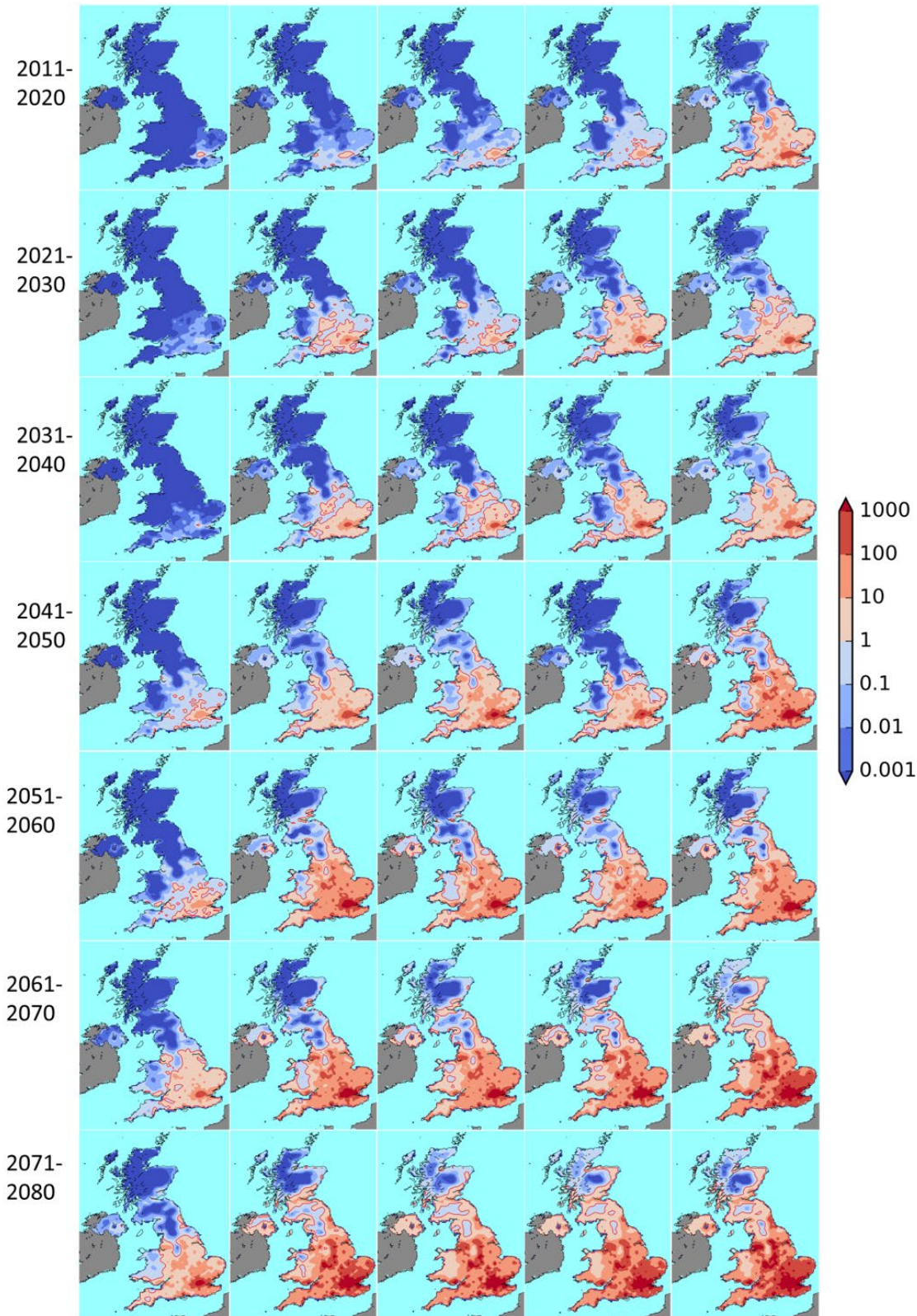
international railway stations and vehicular transport sites across England continues. As *Ae. albopictus* becomes ever more established in continental Europe, it is likely that multiple imports and increased chances of establishment in the UK will trigger the need for enhanced and ongoing monitoring to focus on mosquito management, rather than eradication. At this point, the threat changes from preventing the mosquito from establishing to preventing local transmission of viruses introduced by infected human travellers, by established populations of invasive mosquitoes. Instigating targeted control around imported or local cases, and the employment of mosquito-bite avoidance strategies will become the main options for suppression of transmission.

3.2.1 Future risk of *Aedes albopictus* in the UK

Despite the implementation of successful mitigation measures following detections of *Ae. albopictus* in England to date, there is growing concern that it will eventually become established in the UK and cause outbreaks of dengue and chikungunya, as is being seen in France and Italy. To analyse whether this species could become established in the UK, a model was developed to simulate mosquito dynamics year by year (222). The model is driven by climate variables such as rainfall and minimum and maximum temperatures, as well as human population data. Climate variables were based on UKCP18 projections for the RCP8.5 (high end or 'worst-case') emission scenario on a 12km grid resolution. Human population density was based on the GPWv4 data set (223). For the projections, it was assumed that the total UK population will increase from 67 million to 72 million in the 2070s (224) but the spatial distribution will not change. After having simulated mosquito dynamics each year from 2011 until 2080 for each of the 12 climate runs, suitability for *Ae. albopictus* was calculated by looking at the increase or decrease of eggs from one year to the next. The geometric mean of these changes over 10 years gives the suitability for each decade and each run. The 12 runs were ranked by the total egg number produced to show the range of least to most suitable scenarios.

Simulations suggest that the area around London is already suitable (as of the 2010s) for the mosquito (Figure 12). Other warmer, and densely populated areas around the estuaries of the Thames, the Severn, and the Mersey show up in most simulations as close to but not yet suitable (Figure 12). More mountainous regions are unsuitable. However, simulations based on climate projections suggest that most of England will have become suitable for the establishment of *Ae. albopictus* populations as early as the 2040s or 2050s (Figure 12). In addition, most of Wales, Northern Ireland, and parts of the Scottish Lowlands could become suitable as early as the 2060s or 2070s (Figure 12). These findings demonstrate that once the mosquito gets introduced, it could become well established and a biting nuisance in the southeast of England during future summers. Even if established, however, absolute mosquito numbers would still remain small compared to places in southern Europe (222), limiting the chances of larger outbreaks.

Figure 12. Suitability of the UK for *Aedes albopictus*: suitability indices for individual climate model runs during 2011 to 2080 using RCP8.5 from the UKCP18 climate projections. Left to right: minimum, lower (25th) quantile, median, upper (75th) quantile, maximum suitability for the UK. A suitability index of 1 suggests that one egg this year leads to one egg next year. An index of 100 suggests that one egg this year could lead to 100 eggs next year. The total number of eggs is used for ranking, not the suitable area surface.



3.2.2 Public health significance of invasive mosquitoes in Europe and future risks to the UK: dengue, chikungunya and Zika viruses

Aedes aegypti and *Ae. albopictus* are important vectors of several arboviruses, including dengue, chikungunya and ZIKV. Epidemics of all 3 arboviruses circulate globally, but notably all 3 have caused large epidemics in the Americas in the last 10 years. Both *Ae. aegypti* and *Ae. albopictus* have been involved in local transmission of all these viruses in Europe in recent years. These have generally been associated with small clusters of human cases, but also in outbreaks with a few hundred to a few thousand cases. In 2007, approximately 200 human cases of chikungunya were reported in Italy, transmitted by *Ae. albopictus* (225). A later outbreak in 2017 caused approximately 400 human cases (226) with other small clusters of cases reported sporadically in France (227). In 2012, approximately 2,000 human cases of dengue were reported on the island of Madeira, only 7 years after the establishment of *Ae. aegypti* (228). More recently there have been small clusters of dengue in France and Spain (229) and a small number of ZIKV cases were reported in France in 2019 – the first known transmission of ZIKV in Europe (230). It is clear that the establishment of non-native invasive mosquitoes increases the risk of local transmission of these arboviruses, particularly at a time when epidemics of more than one million cases are occurring so frequently globally and are able to spread rapidly through the movement of infected individuals. Whilst there is currently no local transmission of pathogens between humans and mosquitoes in the UK, climate-driven establishment of non-native mosquitoes could result in local disease transmission occurring in future.

Dengue is the most rapidly spreading mosquito-borne disease globally; incidence has increased 30-fold and it is now endemic in more than 100 countries (231). Approximately 3.9 billion people are at risk of infection with dengue virus (231). In Europe, transmission of dengue fever was first reported in 2010 in Croatia and France; its occurrence has increased throughout Europe, and since 2019, local transmission has occurred in Spain, France and Italy (232). Currently, the only cases of dengue occurring in the UK are linked to travel overseas. Dengue has 4 serotypes that are antigenically similar but do not confer cross-protection. Infection can therefore result in a spectrum of conditions from no symptoms to self-limiting febrile illness with muscle or joint pain, fatigue, nausea, vomiting and or skin rash that usually resolves within 3 to 7 days. Dengue can also cause severe, sometimes fatal illness, characterised by haemorrhagic manifestations, known as dengue haemorrhagic fever.

Modelling studies have suggested that optimal conditions for dengue transmission were observed between 18.5°C and 33.0°C (mean \pm standard error = 28.2°C \pm 2.7) and between 6,262.6mm and 18,585.9mm of precipitation per year (233). Dengue shows little or excessively slow viral development at temperatures lower than 20°C (234), indicating a lower threat to the UK and other temperate regions. Studies have suggested that there is potential for the UK climate to become suitable for dengue in future (235), with one study using CMIP5 atmosphere-ocean general circulation models and RCP8.5 estimating that dengue could become endemic in London during the 2060s (236).

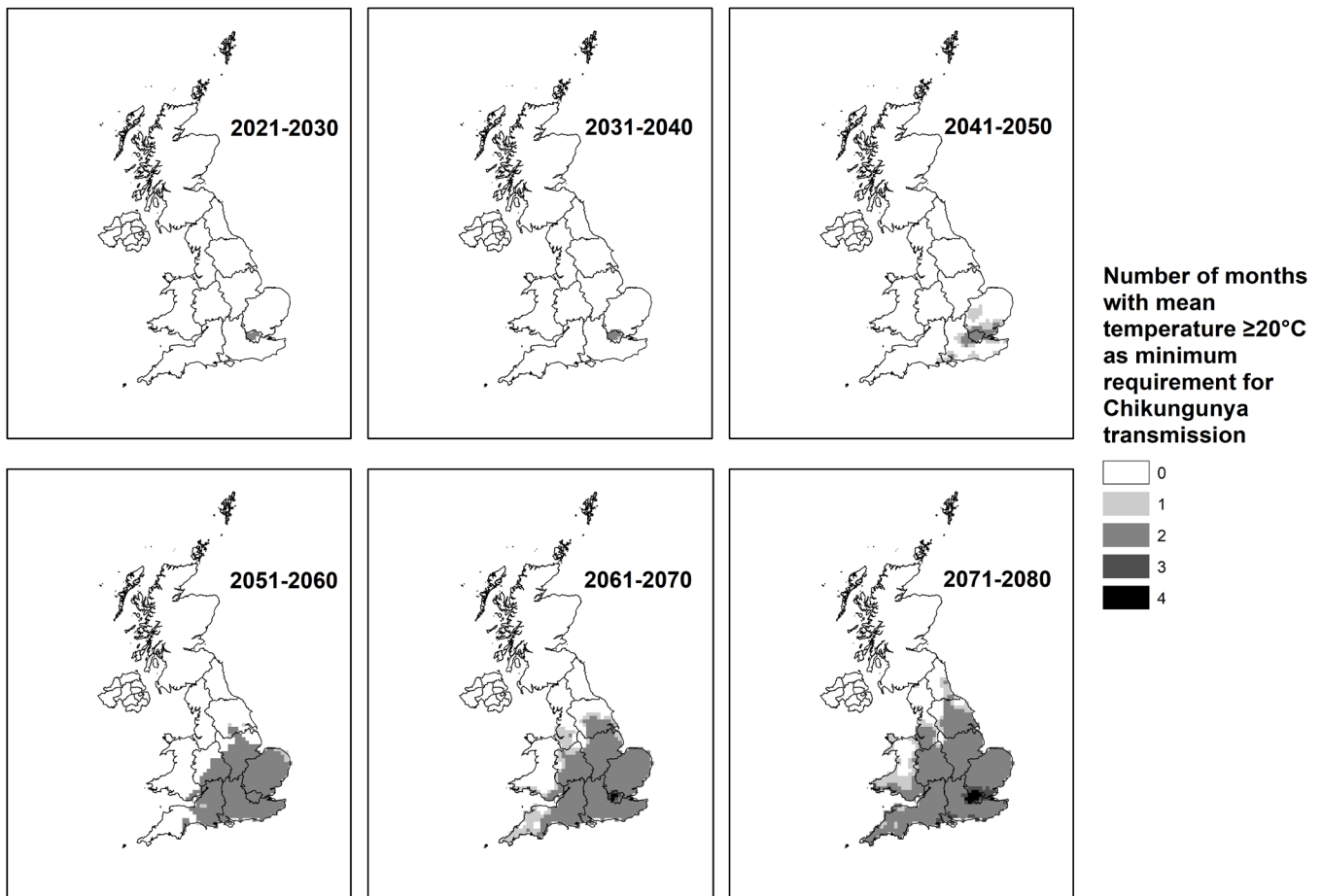
Chikungunya virus was first identified in Tanzania in the 1950s. Since 2004, it has been identified in over 60 countries throughout Asia, Africa, Europe and the Americas (237). Local chikungunya transmission in Europe was first reported during an outbreak in Italy in 2007. Since then, there has been a small number of cases, until 2017, when there was an outbreak in Italy involving 270 confirmed and 219 probable cases (238), and local-acquired cases were also reported in France (237). As with dengue, cases of chikungunya that occur in the UK are linked to travel and there has been no local transmission to date. Chikungunya is largely transmitted by *Ae. aegypti* and *Ae. albopictus*.

A study of chikungunya outbreaks in relation to local monthly mean temperatures (T_{mean}) found that outbreaks started at different temperatures in different geographical localities: 20°C in Italy and Reunion Island, compared with 22°C in India, 24°C in parts of Africa and 26°C in southeast Asia (239, 240). It has been suggested that the minimum threshold for chikungunya outbreaks is a T_{mean} of 20°C (239, 240), with higher transmission risk in areas where T_{mean} exceeds 20°C for at least one month (240). Higher temperatures will lead to shorter extrinsic incubation periods (EIP), increasing the risk of transmission.

The potential length of the intra-annual season of chikungunya transmission in the UK was determined by calculating the number of months where the minimum T_{mean} threshold of 20°C (following (239, 240)) was exceeded (Gillingham, in preparation). UKCP18 regional projections at a 12km grid resolution based on RCP8.5 (high end or 'worst-case' scenario) were used, as this was the only scenario with sufficient spatial and temporal data. Monthly temperatures were extracted per year for each of the 12 sets of predicted temperatures. An average monthly T_{mean} across the decades (2021 to 2030, 2031 to 2040, 2061 to 2070, 2071 to 2080) was calculated, and the number of months where T_{mean} exceeded 20°C was calculated for each decade.

For 2021 to 2040, the predicted T_{mean} is likely to exceed 20°C for 2 consecutive months in parts of London (Figure 13). During the period from 2041 to 2050, the area where T_{mean} exceeds 20°C is likely to expand into other parts of South-East England (Figure 13). During the period from 2051 to 2060, the model indicated that 20°C could be exceeded during one month in parts of eastern England, and during 2 consecutive months across most of southern England, reaching up into parts of the Midlands (Figure 13), and then expanding into parts of northern England and Wales as early as 2061 to 2070. In addition, the predicted T_{mean} could exceed 20°C for 3 and 4 consecutive months in different parts of London (Figure 13). Finally, as early as 2071 to 2080, we found that T_{mean} could exceed 20°C during 4 months in parts of London, 3 months in parts of South East England and along the south coast, during 2 months across most of the remainder of southern England, the Midlands, and areas of northern England, as well as parts of South Wales, and one month across parts of South West and northern England, as well as areas in Mid and North Wales (Figure 13). While these estimates reflect a high end or 'worst-case' warming scenario, they indicate the likely emergence of transmission risk into the UK beginning in the latter half of the century with speed of northern spread linked to rate of warming.

Figure 13. Number of consecutive months where the mean temperature was 20°C or more, as minimum requirement for chikungunya transmission, using the UK Climate Projections 2018 (UKCP18) RCP8.5 pathway (Gillingham, in preparation)

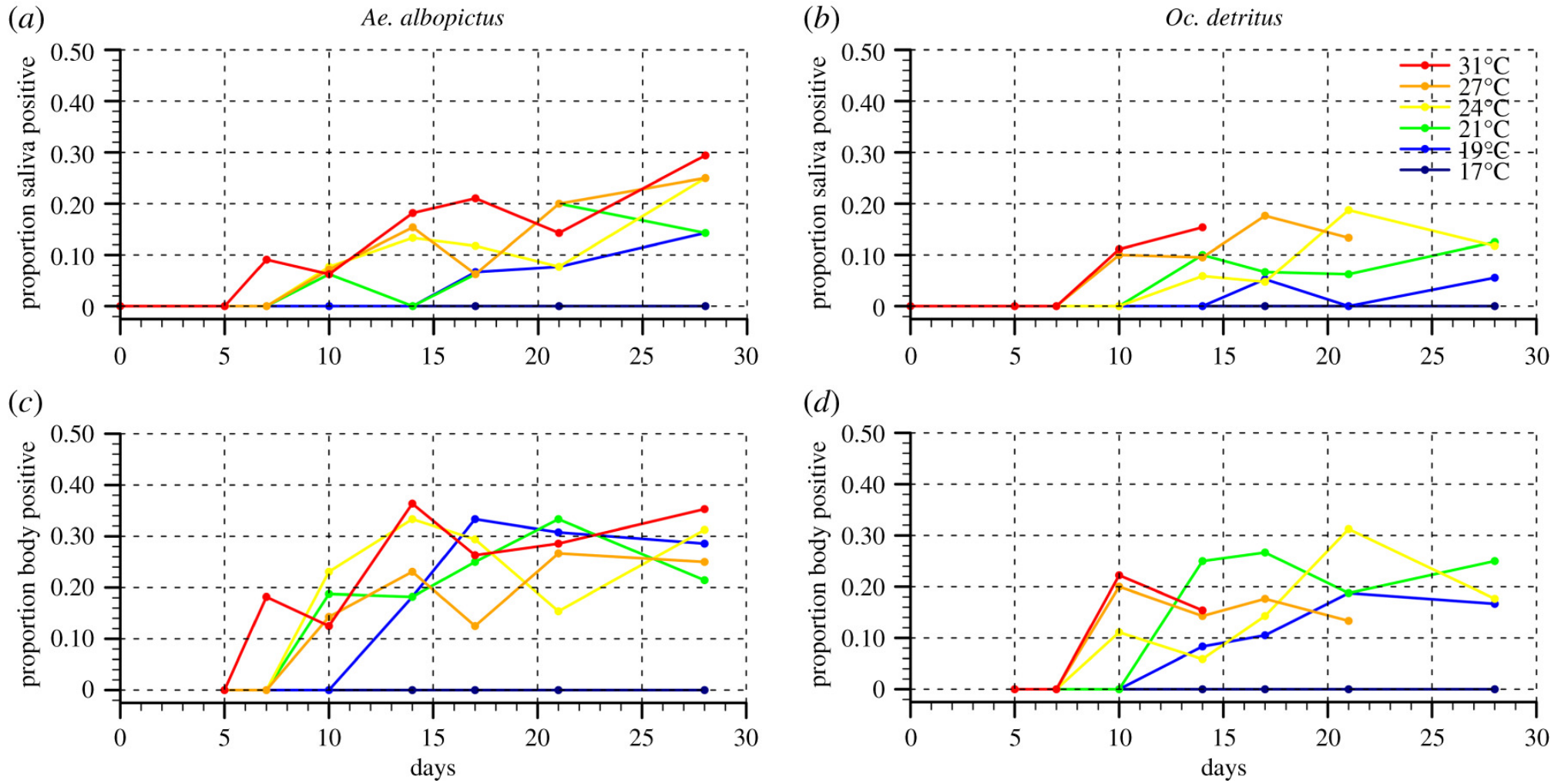


ZIKV was first isolated from monkeys in the Zika forest in Uganda in 1947, and during 1950 to 2014, sporadic outbreaks occurred in parts of Africa, Asia and the Pacific Islands. During 2015 to 2016 an outbreak occurred in South America with cases first identified in Brazil followed by subsequent spread throughout the Americas, Africa, and other regions. The outbreak was declared a ‘Public Health Emergency of International Concern’ by the World Health Organization (WHO) and was associated with more than one million cases and the emergence of congenital Zika syndrome. The outbreak was linked to unusually high temperatures driven by a very strong El Niño event during 2015, where the risk of ZIKV transmission in South America higher during 2015 than any other time between 1950 to 2015 (241). Furthermore, the lack of immunological response against the virus in South America resulted in a significantly larger outbreak than in Africa, where populations have been previously exposed to the virus and were less susceptible to infection (241). ZIKV causes mild infection and is largely asymptomatic in 60% to 80% of cases. It can present with a rash, fever, and other symptoms similar to dengue and chikungunya, but ZIKV can also cause Guillain Barré syndrome (muscle weakness) and congenital Zika syndrome (microcephaly and other congenital abnormalities) (242).

Whilst ZIKV transmission is primarily associated with *Ae. aegypti* and *Ae. albopictus*, mosquito species native to the UK may also be competent vectors. For instance, UK wild-caught *Aedes detritus* were found to be competent for ZIKV transmission between 17°C and 19°C (243), although local transmission is considered unlikely. *Aedes vexans* populations from the USA demonstrated 80% competence at 27°C (244) although this species has very limited distribution currently in the UK. In contrast, no competence was detected for *Cx. pipiens* s.l. or *Cs. annulata* (243).

A comprehensive analysis of the effect of temperature on ZIKV incubation was performed on *Ae. detritus* and *Ae. albopictus*, establishing that the minimum temperature for ZIKV transmission is between 17°C and 19°C (243). Competence tests using 6 different incubation temperatures (17°C, 19°C, 21°C, 24°C, 27°C and 31°C) each at 8 different durations (0, 5, 7, 10, 14, 17, 21 and 28 days post-infection) were performed (Figure 14) (243). Risk across the UK and Europe from *Ae. albopictus* (the more competent of the 2 vectors) was modelled, both in current climatic conditions and in future projected conditions (Figure 15; Figure 16).

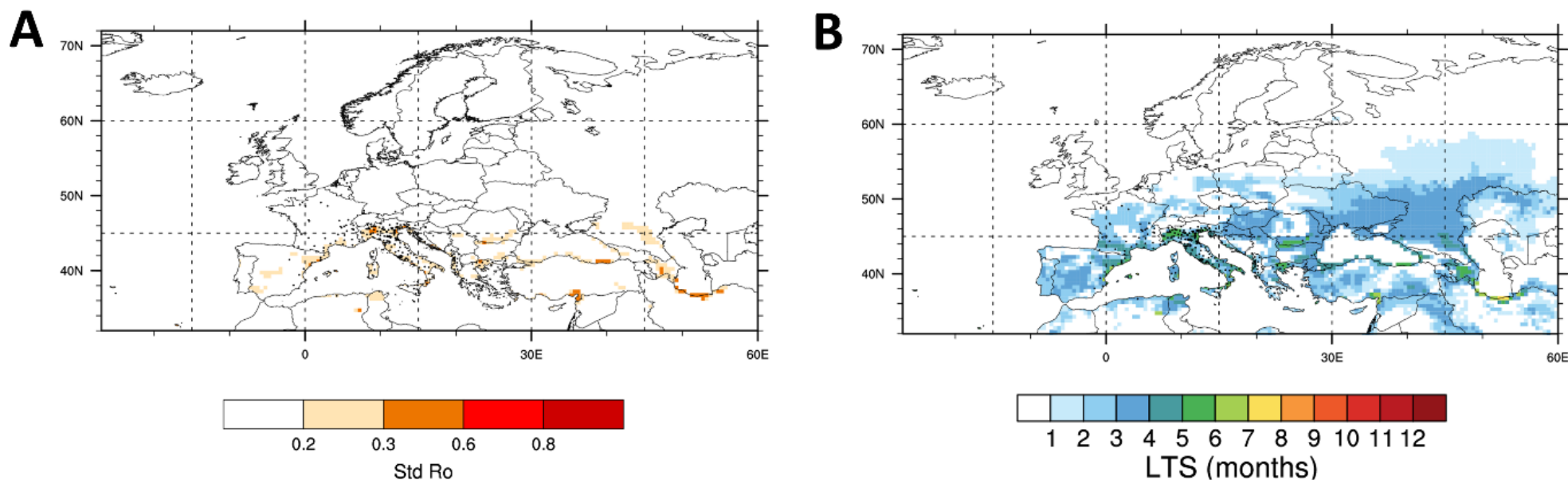
Figure 14. Proportion of total *Aedes albopictus* and *Aedes detritus* saliva (a,b) and bodies (c,d) positive for ZIKV at 6 temperatures (17°C, 19°C, 21°C, 24°C, 27°C and 31°C) and 8 time points (0, 5, 7, 10, 14, 17, 21 and 28 days post-infection) (243)



$R_0(T)$ is an R_0 estimate where the temperature dependent EIP obtained from our laboratory transmission experiments (243) is incorporated into the R_0 model. The final $R_0(T)$ estimate is then standardized between 0 and 1 to be consistent and comparable with previous models. Using the laboratory data from Figure 14, annual mean standardized $R_0(T)$ estimates for *Ae. albopictus* potential to transmit ZIKV across the UK and Europe were calculated. This was expressed as both annual $R_0(T)$ estimates (Figure 15A), and as an estimate for the number of months at which the temperature and rainfall were sufficient for ZIKV transmission (Figure 15B). Global Historical Climatology Network Climate Anomaly Monitoring System (GHCN-CAMS) gridded temperature data and the Global Precipitation Climatology Centre (GPCC) global rainfall data was used to calculate and model these values. There is significant $R_0(T)$ and duration of transmission season across southern Europe (Figure 15). The black dots on the maps indicate observed *Ae. albopictus* in the area. There is clearly a strong correlation between *Ae. albopictus* presence and modelled ZIKV transmission risk, indicating that as climatic conditions become suitable for *Ae. albopictus*, ZIKV transmission risk also becomes significant. The simulated seasonal transmission of ZIKV by *Ae. albopictus* over southern Europe is consistent with autochthonous cases of ZIKV in Hyères, near to Marseille in south-eastern France (245). Furthermore, the simulated hotspots match areas where recent local transmission of dengue or chikungunya viruses by *Ae. albopictus* have been observed in Europe, for example: the 2007 chikungunya outbreak in Ravenna, Italy; suspected dengue fever in Cadiz, southern Spain in 2018; and the reported cases of dengue in south-eastern France in 2010, 2013, 2014 and 2015.

Figure 15. Simulated $R_0(T)$ and length of ZIKV transmission season in Europe

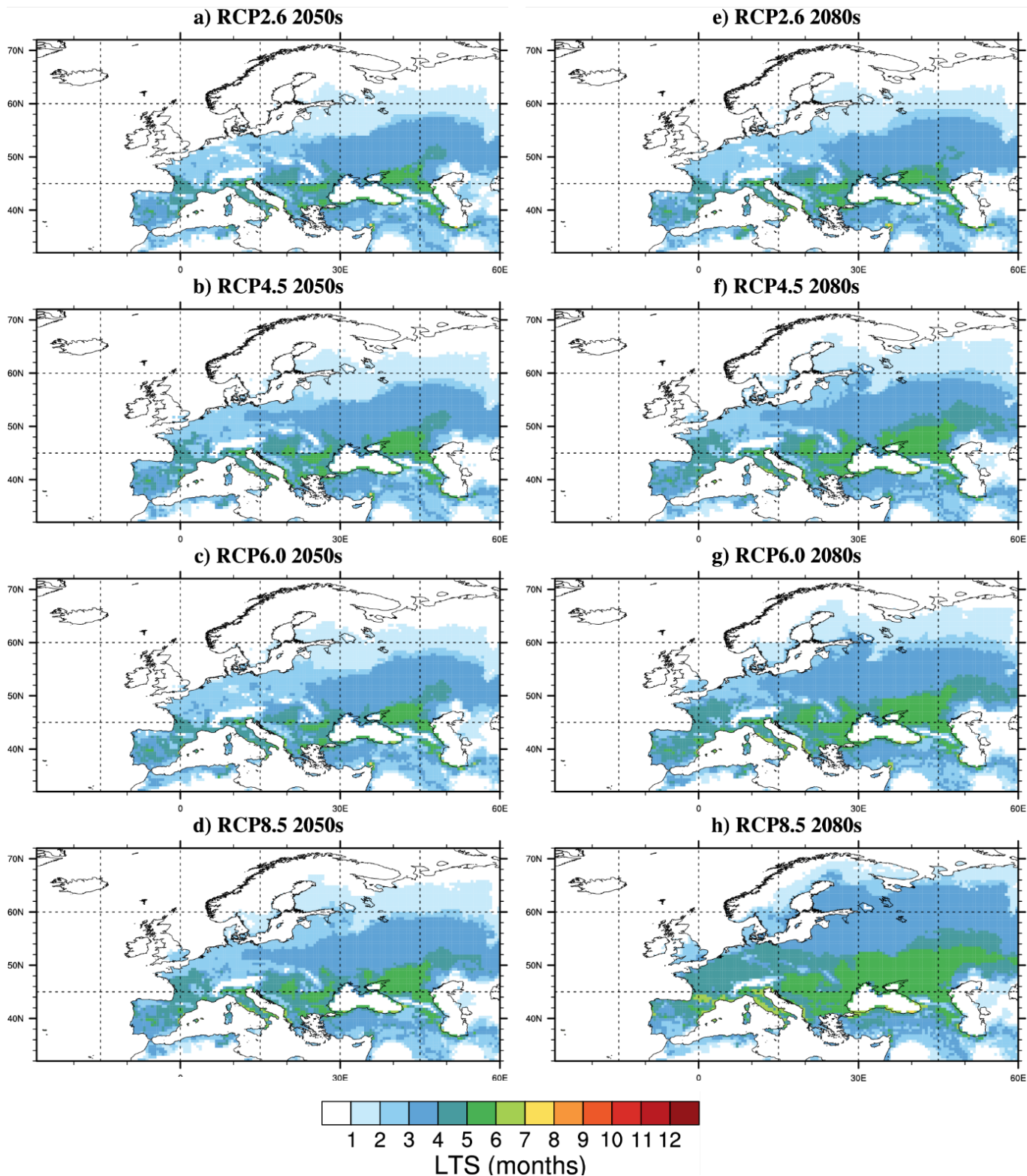
(A) Annual mean standardized $R_0(T)$ estimates for *Ae. albopictus* potential to transmit ZIKV. This is carried out for the historical context (1980 to 2010 average) based on observed rainfall and temperature data for Europe (243). (B) Simulated length of the ZIKV transmission season (LTS in months) is based on observed rainfall and temperature data (1980 to 2010) for Europe (A and B). Black dots represent observed presence of *Ae. albopictus* (246).



Hence, future risk as the climate changes was modelled to estimate when and where ZIKV transmission may become likely in the UK and Europe. The Calibrated General Circulation Model (GCM) temperature outputs from the ISI-MIP project were utilized to assess future risk of ZIKV transmission. The RCP2.6, RCP4.5, RCP6.0 and RCP8.5 emission scenarios (from the lowest to the highest emission scenario) were used (Figure 16). ZIKV transmission risk is seen to increase significantly in the future over southern and eastern Europe, especially under the highest emission scenarios and for the 2080s (Figure 16: d, g and h). ZIKV transmission by *Ae. albopictus* could increase over high-altitude regions, consistent with expected impacts of climate change on malaria (247) and other studies which focus on similar future trends (248, 249).

Figure 16. Simulated length of the ZIKV transmission season by *Ae. albopictus* over Europe under future climate scenarios

This is carried out for the 2050s (2040 to 2059 average), left column (a, b, c, d) and the 2080s (2070 to 2089 average), right column (e, f, g, h), from the lowest (RCP2.6, top, a, e) to the highest (RCP8.5, bottom, d, h) emission scenario.



4. Discussion and implications

It is difficult to attribute changes in the distribution and abundance of VBDs directly to climate change. This is particularly challenging for tick-borne disease systems where climate can impact upon the vector directly, as well as indirectly affecting hosts, habitats and human behaviour. It is therefore difficult to ascertain linear relationships between increased temperature and cases of tick-borne infections, such as LB. The relationship is further complicated by human interventions in wildlife management and land-use practices, including those intended to mitigate the effects of climate change, as well as tick-borne infections that have transmission cycles involving wildlife hosts. Increased temperatures will undoubtedly impact on the survival ability of non-native ticks, such as *Hy. marginatum*, and interact in complex ways with emerging tick-borne viruses. For mosquito-borne diseases, there are available studies and data on climate predictions of non-native mosquito survival and abundance and the extrinsic incubation of viruses in mosquitoes. Very hot summers have been implicated in the transmission of mosquito-borne arbovirus outbreaks previously. Mosquitoes can quickly adapt to their surroundings and, provided humans continue to provide routes of dispersal into new areas, then warmer temperatures will continue to favour the establishment and spread of invasive mosquitoes. Adaptation solutions, such as land use change for flood alleviation and water storage, are likely to impact upon native mosquito populations, and household water storage is likely to provide increased habitat for invasive mosquitoes. Furthermore, extreme weather events such as droughts and flooding are likely to impact upon mosquito populations, more so than tick populations.

The 'Third Climate Change Risk Assessment' (CCRA3) has given the risk to health from VBDs in the UK an urgency score of "more action needed" (250), meaning that current adaptation is insufficient to reduce risks. Once a non-native vector or pathogen is established, it would be difficult for it to become eradicated. The UK's third National Adaptation Programme (2023 to 2028) (251) includes actions to avoid the potential impacts of VBD outbreaks, including (i) improving vector and disease surveillance to detect invasive species or cases of VBDs early; (ii) regularly updating risk assessments of cases or outbreaks; (iii) increasing preparedness for response to both vector and disease outbreaks through contingency planning, habitat management plans and targeted human, animal and vector surveillance; and (iv) understanding more about the impacts of weather and climate on vectors and their pathogens through modelling. It is vital to remember that other environmental changes, either as adaptation or mitigation for climate change, particularly those geared towards promoting biodiversity, flood alleviation and urban greenspace management, will have an indirect impact on vector-borne disease systems, independent of, and often interacting with, the effects of climate change.

Current policies on VBDs are limited to outputs from the Human Animal Infections Risk Surveillance (HAIRS) group, which highlights the need for contingency planning. However, these are to address an emerging disease risk, rather than to directly address the impacts of climate change. There are current contingency plans for VBDs which include invasive mosquitoes (221) and for WNV (to be published by 2024). UKHSA also recently established a

VBD horizon scanning group to bolster preparedness and response to current and future VBDs, bringing together experts from the wide range of disciplines central to VBDs.

Priorities for research and public health include greater focus on climate or weather-based modelling for both vectors and vector-borne pathogens in the UK in future, using a range of different projection scenarios. The modelling included in the current chapter has focused on RCP8.5, which reflects a worst-case scenario, with lower warming scenarios more likely. It was not possible to conduct modelling using other RCP data (for example, RCP2.6, RCP4.5) as data is currently not available at the required temporal or spatial resolutions. The results using RCP8.5 are thus a reflect of a worst-case scenario of rapid warming with no adaptation or mitigation.

As climate change is likely to lead to the establishment of non-native vectors and the emergence of novel VBDs in the UK, there needs to be improved surveillance to detect invasive species and enhanced sero-surveillance studies to detect exposure to emerging vector-borne pathogens. There should also be increased preparedness for responding to vector and disease outbreaks through contingency planning, habitat management plans and targeted human, animal and vector surveillance. Finally, there is a need to conduct field-based studies on ecological drivers for changes in vectors and VBDs due to climate and environmental change (including those listed above). As the UK moves into a period of significant land-use change and the promotion of environmental policies that favour biodiversity in both rural and urban areas, it is important to consider and understand the indirect impact such changes may have on vectors and VBDs, independent of the effects of climate.

Acronyms and abbreviations

Abbreviation	Meaning
CCHFV	Crimean-Congo haemorrhagic fever virus
EIP	extrinsic incubation periods
HECC	Health Effects of Climate Change in the UK report
LB	Lyme borreliosis (also called Lyme disease)
LIV	louping ill virus
MIR	minimum infection rate (number of infectious mosquitoes per 1,000 adult females)
RCP	representative concentration pathways
Spp.	species (plural)
TBEv	tick-borne encephalitis virus
TSS	Tick Surveillance Scheme
UKCP	UK Climate Projections
UKHSA	UK Health Security Agency
VBD	vector-borne diseases
WNV	West Nile virus
ZIKV	Zika virus

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UKHSA is responsible for protecting every member of every community from the impact of infectious diseases, chemical, biological, radiological and nuclear incidents and other health threats. We provide intellectual, scientific and operational leadership at national and local level, as well as on the global stage, to make the nation health secure.

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