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Review Paper

Impact of drought on vector-borne diseases – how does one manage the risk?

L. Brown [a,*], J. Medlock [b], V. Murray [a]

[a] Extreme Events and Health Protection, Public Health England, UK
[b] Medical Entomology and Zoonoses Ecology Group, Microbial Risk Assessment, Emergency Response Division, Public Health England, UK

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ABSTRACT

Objectives: This article aimed to review all literature on drought and vector-borne disease to enable an assessment of the possible impact of drought on the changing risk of vector-borne diseases in the UK.

Study design: A systematic literature review was performed.

Methods: Using a search strategy developed from a combination of terms for drought and selected outcomes, the authors systematically reviewed all available literature from 1990 to 2012 on the impact of drought on vector-borne diseases. The following databases were searched: PubMed, Web of Science, and EMBASE. After reviewing the abstracts, 38 articles were found to fit the inclusion and exclusion criteria.

Results: Evidence found drought followed by re-wetting can have a substantial effect on water table levels, vegetation, and aquatic predators; all factors which influence mosquito populations. Several studies found an association between a drought during the previous year and West Nile virus incidence. Urban mosquito vectors of dengue virus and chikungunya virus are adaptable by nature and are able to exploit a multitude of additional aquatic habitats created as a response to drought (i.e. water storage containers). Tick populations are likely to be negatively affected by drought as they are dependent upon high levels of humidity and soil moisture.

Conclusions: Further research is needed to identify public health interventions and environmental control measures for an invasive mosquito problem or arthropod-borne disease outbreak in the UK.

Introduction

Since the beginning of the 21st Century, Europe has seen the continued spread and establishment of invasive mosquitoes such as *Aedes albopictus* in most Mediterranean countries,[1] as well as outbreaks of invasive-*Aedes* transmitted chikungunya virus (CHIKV) in Italy and dengue virus (DENV) in Madeira.[2] Large-scale outbreaks of West Nile virus (WNV) have become more common in Eastern Europe, and Usutu virus (USUV) has emerged in Central Europe.[3] The emergence

* *Corresponding author*. Public Health England, Wellington House, 133-155 Waterloo Road, London SE1 8UG, UK. Tel.: +44 (0) 20 7811 7142; fax: +44 (0) 20 7811 7759.
E-mail address: lisa.m.brown@phe.gov.uk (L. Brown).

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of bluetongue virus and Schmallenberg virus in Northern Europe, including the UK, has highlighted vector-borne diseases as an issue for UK public and veterinary health. These events raise questions as to which vectors and pathogens may appear next in the UK and what role a changing climate may have in driving these changes. A report by Public Health England on the health impacts of climate change highlighted key issues for vector-borne diseases, and it was clear that little research had been done on the impact of drought on vector-borne disease risk.[4]

In the UK, summers are predicted to be drier by up to 40% in the southwest, with a general south to north gradient by 2080.[5] Furthermore, there is medium confidence that droughts will become more intense in the 21st Century in Southern Europe and the Mediterranean as well as Central Europe, because of reduced precipitation and/or increased evapo-transpiration.[6] Drought has an effect on all components of the water cycle, from a deficit in soil moisture and groundwater levels to low stream flows and dried up rivers. Droughts are slow-onset phenomena, generally develop over an extended period of time, and can be geographically extensive.[23] Stanke et al.[23] found the lack of standardization in the definition of drought is reflected by over 150 published definitions. Generally and in the context of this review, drought can be defined as a deficit of water from the norm for a given spatial area that is the result of constantly below average precipitation. In some countries, drought can be associated with the El Niño Southern Oscillation (ENSO). ENSO is comprised of changes in sea temperatures in the Pacific Ocean (El Niño) and changes in atmospheric pressure across the Pacific basin (Southern Oscillation).[7,8] The association between ENSO and drought has been established in North-eastern Brazil, south-eastern Africa, South Asia, Indonesia, and Northern Australia.[8] It has been documented that droughts are twice as frequent in the year following the onset of El Niño than during other years.[23]

Precipitation changes are known to affect the reproduction, development, behaviour, and population dynamics of arthropod vectors, their pathogens, and non-human vertebrate reservoirs.[9] Recent research suggests that drought may lead to subsequent increases in mosquito numbers and disease outbreaks.[10,11]

Aims and objectives

There has been growing interest in the UK regarding the potential establishment and spread of invasive mosquito species,[12] the involvement of these species in the transmission of pathogens,[13,14] as well as the possible role of native mosquitoes in transmitting emerging pathogens.[15] This article aims to review literature on drought and vector-borne disease (relevant to the UK) to enable an assessment of the possible impact of drought on the changing risk of vector-borne diseases in the UK by specifically addressing the following topics:

- the impact of drought on aquatic habitats for mosquitoes; specifically the impact of wetland drying then re-wetting in relation to the consequent potential for increase in mosquito numbers;
- the impact of drought in relation to WNV outbreaks in North America and Europe;
- the impact of drought on urban *Aedes* mosquito vectors of CHIKV and DENV;
- the association between ENSO and Rift Valley fever virus (RVFV) outbreaks in Africa and Arabia; and
- the impact of drought on tick populations, particularly *Ixodes ricinus*.

Methods

A literature review was carried out addressing the specific issues regarding drought and its impact on disease vectors and their pathogens. A search strategy was developed using combination of terms for drought and selected outcomes in the title, keywords, or abstract (Table 1).

Databases used

The following databases were searched: PubMed, Web of Science, and EMBASE. Expert advice was sought for further sources of literature, and references from extracted studies were hand-searched.

Inclusion criteria

- Papers published from 1 January 1990 to 1 November 2012.
- Studies conducted in any country. This systematic literature review included globally published literature because Europe experiences a wide range of climate and geographical variation.
- Papers in all languages with English abstracts.

Exclusion criteria

- Papers describing drought alone, with no mention of vectors.
- Drought meaning shortage unrelated to climate; studies on dry/arid climates unless drought was noted as an unusual occurrence in the normal climate variability of the area.
- Papers on unrelated subject areas; such as, biochemistry, molecular biology, and genetics.
- Grey literature.
- Papers regarding ENSO and other vector-borne diseases besides RVFV, unless the paper explicitly mentioned drought.

Table 1 – Search strategy.

Exposure: drought OR El Nino OR ENSO OR El Nino Southern Oscillation OR 'rainfall after drought'
AND
Outcome: aedes albopictus OR aedes aegypti OR arbo* OR arthropod* OR chikungunya OR culex modestus OR culex pipiens OR dengue* OR Ixodes ricinus OR lyme borreliosis OR malaria OR mosquito* OR outbreak OR rickettsiae OR Rift Valley fever virus OR sindbis* OR tahyna* OR tick* OR vector* OR West Nile virus

Study selection

Result details were checked for duplicate citations, and any identified duplicates were excluded. Full papers were identified following screening of all titles and abstracts by two study authors (LB and JM). These papers were further reviewed for eligibility and inclusion in the review. The initial search found 2055 relevant articles. After reviewing the abstracts, 62 full-text articles were examined in more detail for eligibility. Of these 62 articles, 38 articles were found to fit the inclusion and exclusion criteria. Some articles and gray literature not meeting the specific inclusion criteria were incorporated into the relevant section to give a better contextual outline.

Results

Climate is one of many variables known to affect the rates of vector-borne diseases. The potential for drought to impact vector-borne diseases rests with climatic influences on the ecology of the arthropod vectors and animal hosts, and on the life cycles of the disease-causing pathogens they carry. Drought can influence numerous aspects of a vector's life cycle: survival, population numbers, behaviour, distribution, and vector–pathogen–host interactions. For example, during drought conditions certain mosquito species might be favoured as larger pools become shallower and the velocities of rivers and canals decrease, thereby increasing the extent of aquatic sites.[4] The impact of drought on mosquitoes is examined extensively in this review, because mosquitoes are one of the most important arthropod vectors involved in vector-borne pathogen transmission.

Drought and the consequent increase in mosquito numbers following re-wetting

Some wetlands, known as 'permanent wetlands', are intended to remain wet at all times; thereby retaining standing water and enabling mosquito predators (mostly invertebrates, but also fish and amphibians) to complete their life cycles, reach high densities and generally keep immature mosquito numbers contained.[10,16,17] In contrast, 'temporary wetlands' are generally expected to dry yearly, and in many cases there is an assemblage of mosquito predators and competitors that are well adapted to predictable drying which limit mosquito abundance. However, for wetlands that unnaturally dry out, the population of mosquito predators and competitors can be lost, thus enabling, after re-wetting, a rapid re-colonization of the wetland by mosquitoes allowing them to reach high population densities.

Chase and Knight[10] found that mosquito outbreaks were associated with droughts during the previous year, confirming that droughts reduce mosquito predators and competitors allowing mosquito abundance to increase the following year. Until recently in the UK and Europe there has been little to no guidance for wetland managers regarding the mitigation of a mosquito problem in an environmentally-sensitive way.[17] Published and unpublished field-based research by Public Health England entomologists has shown that both freshwater and brackish water habitats in the UK subject to drying and re-wetting contribute to large numbers of adult mosquitoes within the same year.[18,19] In freshwater habitats drought may act on habitats by promoting the laying of drought-resistant eggs by *Aedes/Ochlerotatus* mosquitoes in areas subject to re-immersion. The surface area available for oviposition is reduced in areas that remain wet all year. The eggs remain in low-lying areas waiting for re-immersion, with evidence that they can remain viable out of water for up to two years. Furthermore, in permanent habitats (such as ditches) that dry unnaturally, the loss of predators is profound, and the rapid increase in Culicine mosquitoes is significant, with evidence of a rapidly changing mosquito fauna following a drought event.[19] The loss of predators during a drought promotes the rapid colonization by opportunist mosquitoes following re-wetting as they exploit new habitats free from population control. In brackish water habitats, the influence is more likely due to the act of flood tides, rather than drought.[18]

In Florida, spring drought has been shown to concentrate *Culex nigripalpus*, a vector of both WNV and St. Louis encephalitis virus (SLEV) in humid vegetated areas where birds are present.[20–22] Studies showed that subsequent summer rainfall raises the humidity, promotes host-seeking, and enables the subsequent dispersal of infected adult mosquitoes into vegetated areas they had previously avoided during the drought.[21,22] Drought and subsequent re-wetting was shown to have an effect on mosquito populations and possibly mosquito-borne disease risk. Both the 1977 and 1990 SLEV epidemics in Florida followed this pattern. However, if a drought persists for too long the vectors may not survive, thus reducing SLEV and WNV transmission. Overall, owing to the fact that drought increased contact between birds and SLEV-infected *C. nigripalpus*, the drought event was seen as a necessary precursor for increased human SLEV incidence in Florida.[21]

Drought and West Nile virus

West Nile virus (WNV) is a mosquito-borne flavivirus transmitted by mosquitoes. Its enzootic cycle occurs between birds and ornithophilic mosquito vectors. Mosquitoes that feed on birds and other animals (e.g. horses) and humans are known as bridge vectors. The principal mosquito species that transmit the virus are member of the genus *Culex*. The principle bridge vector of WNV in Southern Europe, *Culex modestus*, was recently found to be established in the UK in the North Kent Marshes[15] and more recently in the Cambridgeshire fens.[24]

In wetlands, drought causes a decrease in the available habitat for mosquitoes, as well as the assemblages of predators and competitors. In those aquatic habitats that dry out, the predator populations are lost and the re-colonizing mosquito populations following re-wetting are able to increase rapidly in the absence of this natural control mechanism.[25] Furthermore, as wetlands decrease in size at the onset of a drought event, congregations of birds in areas with WNV-infected mosquitoes at the remaining wetlands will likely act to drive the enzootic transmission of the virus and the subsequent risk to animals and humans. Dry years in Illinois were shown to more likely result in higher minimum WNV infection rates in humans, and the combination of higher temperatures and less rainfall were highly associated with the highest minimum WNV infection rates and/or with human cases. Additionally, in Mississippi, an inverse relationship existed between county-level human WNV incidence and total annual precipitation from the previous year.[26]

Similar findings have been reported in Europe. During summer 2008 in north-eastern Italy, an outbreak of WNV occurred, with 23 equine cases and three human cases of the neuroinvasive form confirmed by laboratory tests.[28] In Italy, *Culex pipiens* has been implicated as the main WNV vector. *C. pipiens* thrive during drought conditions by exploiting both larval habitats with high organic content (a consequence of drying) and also in artificial containers not reliant on rainfall.[29] Another mosquito-borne flavivirus, Usutu virus (USUV) was also found to be circulating among mosquitoes and birds. In Italy, an association was observed between USUV-positive mosquito pools and drought conditions.[30] Similar results were obtained for WNV, thus supporting previous studies from the US evidencing the positive influence of drought and warm temperatures on WNV circulation.[11,22,25–27,29,31,32] Calzolari et al.,[30] concluded that these results were due to the concentration of birds and mosquitoes near water sources; as well as, the possibility that drought may affect mosquitoes by influencing their vector competence.[33]

Smartt et al.,[33] noted that lack of oviposition sites facilitated by drought can force *C. pipiens* to retain their eggs. When compared with mosquitoes that did oviposit, mosquitoes that were forced to retain their eggs showed significantly higher virus titres early after WNV infection as well as trends toward higher virus titres at later time points, thus potentially increasing their vector competence. This also may suggest a possible immune response against WNV that is stimulated by oviposition.[34] Additionally, egg retention vs oviposition did not significantly affect WNV infection, dissemination, or transmission rates under the conditions of the test. The management of drying and drought-affected wetlands during a WNV incursion will be crucial in controlling the endemicity of the virus and the exposure of humans to virus-infected mosquitoes.

Drought and urban mosquito vectors

DENV is transmitted between humans by *Aedes (Stegomyia)* mosquitoes. Notably these mosquito species are prevalent in urban areas where they survive in close association with humans by exploiting a range of containers as aquatic habitats.[35] The storage of water in urban areas during a drought event can impact significantly on the availability of aquatic habitats for the mosquito vectors.

In 2009, reduced rainfall in southeast Australia placed communities on increasing water restrictions.[36] The government encouraged the installation of large domestic water tanks (>3000 L) in cities throughout the region. Beebe et al.[36] experimentally concluded that human adaptation to drought through the installation of water tanks posed a substantial risk to the population by providing potential, stable mosquito larval habitats and leading to the reintroduction of *Aedes aegypti* from Queensland along with the associated DENV.

In Brazil, periods of drought promoted DENV vector abundance by firstly contributing to an increase in stored water among local residents and secondly a coincident drought-associated cholera outbreak interrupted local DENV surveillance activities.[37] It is widely recognized that a change in human behaviour towards increased water storage, an increased number of artificial containers, as well as an absence of window screening and air conditioning can increase exposure to *A. aegypti* and hence facilitate DENV expansion.[35]

CHIKV shares many characteristics with DENV, including the ability to exploit humans as the sole amplifying host, with both vectored by *A. aegypti* as the principle vector and more recently *A. albopictus*.[35] In the Republic of Yemen in 2011, water scarcity and the lack of infrastructure in some urban areas required the regular storage of water for household and potable use; thus promoting aquatic habitats for *A. aegypti*.[38] Heavy rainfall following the dry season led to fluctuations in water levels favouring an increase in abundance of *A. aegypti* eggs and promoting transmission of CHIKV.

A CHIKV outbreak occurred during a severe drought period 2005–2007 in East Africa and the western Indian Ocean islands. A severe drought across the East African region led to the widespread container storage of water among households. The unprotected water storage allowed *A. aegypti* to reproduce in large numbers and permit the establishment of Central/East African genotype CHIKV in densely populated areas. Additionally, elevated temperatures facilitated virus amplification and increased the vector capacity of the mosquitoes.[39,40] Vector competence was further increased, as well as the potential for the virus to extend its geographic range, due to a mutation in the virus which increased virus replication and dissemination in *A. albopictus*.[41] Following the CHIKV epidemics in Indian Ocean areas (2005–2007), the mutated virus was imported into Italy by a traveller returning from India. More than 200 locally acquired cases of CHIKV were transmitted by Italian populations of *A. albopictus*.[42] Autochthonous CHIKV infections in northern Italy demonstrate the ability of CHIKV to be transmitted even in temperate climates.

More recently, an outbreak of dengue in Madeira, Portugal in 2012 involving more than 2000 cases (transmitted by *A. aegypti*) and the autochthonous cases of DENV in France and Croatia in 2010 (transmitted by *A. albopictus*), raise concerns about the role of established invasive mosquito species as vectors of endemic and exotic viruses in Europe. The establishment of *A. albopictus* presents the major threat in Europe having now been reported in >20 European countries and having established widely in Italy, as well as parts of France, Spain, and other locations in the Mediterranean region such as the Adriatic coast.[1] This species, along with other invasive *Aedes* species with vector potential are frequently imported into Europe on used tyres with numerous examples of imports into Northwest Europe,[1] specifically the Netherlands[43] and Belgium.[44] Female *A. albopictus* lay their eggs above the water line in a range of container habitats. These eggs are able to withstand desiccation and prolonged periods out of water. In Italy rainwater gullies on roads are designed with catch basins and these provide an additional habitat for *A. albopictus*. These may not wash out regularly during drought hence providing long-term aquatic habitats for urban mosquito species.

Furthermore, the establishment of *A. aegypti* in Europe could potentially have a public health impact. *A. aegypti* can utilize sheltered sites in domestic settings which can provide protection from drought and other environmental conditions. Because this species is highly adapted to urban environments, it has proven difficult to control in Madeira[1] and was the primary vector involved in the most recent DENV outbreak.[2]

Also of concern is another container-breeding mosquito, *Aedes japonicus*, which is currently established in Switzerland,[45] Germany[46,47] and Belgium.[48] Studies have demonstrated that this species is able to become a competent vector and has the potential to become involved in disease transmission, particularly WNV.[1] Ongoing surveillance of invasive mosquitoes at UK ports of entry and at used tyre companies are imperative to prevent, identify and control incursions of these mosquitoes, which have been shown to establish in a climate similar to the UK. Furthermore, following incursion and possible establishment of these mosquitoes, public information on the appropriate management of household water storage (water butts etc.) will be required.

El Niño Southern Oscillation and Rift Valley fever virus

Rift Valley fever virus (RVFV) is maintained by transovarial transmission in the eggs of floodwater mosquitoes, especially *Aedes* spp.[49] When *Aedes* spp. mosquitoes infect domestic animals it allows various *Culex* spp., which are also capable of transmitting RVFV, to transmit the virus to a wider area beyond the original outbreak.[50] RVFV outbreaks have been shown to be closely associated with climate anomalies.[50] RVFV transmission is enzootic during most years, but epizootic during wet years following droughts.[35] Wet years inundate several previous seasons of drought-resistant, virus-infected mosquito eggs, giving rise to a large number of infected mosquitoes.

El Niño is the term used to describe the extensive warming of the normally cold surface temperatures of the central and eastern Pacific Ocean.[50] The Southern Oscillation describes the above-average atmospheric pressures in Indian Ocean associated with below-average atmospheric pressures in the Pacific (and vice versa).[23] This dramatic change shifts the normal atmosphere-ocean circulating pattern in the tropics, and results in above-normal rainfall in the normally dry East Africa. During El Niño-Southern Oscillation (ENSO), regions of Kenya that are typically dry (less than 700 mm of annual rainfall) receive above-normal rainfall which results in extensive flooding.[40,50,51] For example, East Africa experienced above-normal rainfall from September–December 2006 which flooded low-lying wetlands known as dambos. Dambos are the primary habitats of *Aedes* spp. mosquitoes pre-infected with RVFV from previous epizootics. Prior to above-normal rainfall, the dambos must be damp in order for oviposition to take place. The drying of the dambos followed by heavy rains which flood them results in a rapid increase in mosquitoes, as well as enhanced and sustained vector survival because of the emergence of protective vegetated habitat. Both wild and domesticated ruminants are driven by herdsman to these sources of water and vegetation; thereby bringing susceptible hosts into close proximity with the infected mosquitoes.[35] Wild ungulates may birth calves at this time, producing a cohort of non-immune hosts. Furthermore, a spatial shift of RVFV was observed from Eastern to Southern Africa in tandem with the phase shift of El Niño to La Niña.[52] In areas where El Niño can be reliably associated with droughts, forecasts can be used to provide advance warning of the increased risk of RVFV.[8]

Originally, RVFV was thought to be restricted only to Africa; however, it was reported in the Tihama region of both Saudi Arabia and Yemen in September 2000.[49] In Egypt, *Ochlerotatus caspius* and *C. pipiens* are thought to be the most important vector species, although the former may not be involved in vertical transmission. This documented expansion of RVFV beyond sub-Saharan Africa into Egypt and the Arabian Peninsula makes RVFV a likely candidate for further expansion; especially where *Aedes vexans*, *O. caspius*, and *C. pipiens* are present and immunologically naïve animal species exist. RVFV has a high potential to impact wildlife, domestic animals, and human health and failure to contain RVFV could seriously impact human and veterinary health in Europe. However, current controls on imported livestock into the EU including the UK is likely to minimize the risk of RVFV transmission in Europe. Furthermore, a low density of *A. vexans* and restricted distribution of human-biting *C. pipiens* in the UK suggests that the current risk of RVFV transmission to humans in the UK is low.

Drought and tick populations

Currently the most important tick and disease vector species in the UK and Europe is *I. ricinus* (sheep/deer tick). *I. ricinus* is a vector of *Borrelia burgdorferi s.l.* to humans and tick-bite fever and louping ill to animals. The ability of ticks to maintain moisture balance and blood host availability is affected by environmental and ecological factors.[52] The impact of drought therefore is likely to challenge the moisture balance of *Ixodes* ticks. In the US, studies on *Ixodes scapularis* in Illinois in a year following drought found that larval densities were significantly lower compared to the eight-year average at the site.[53] Drought acted by severely damaging the vegetation (grasses, forbs, and shrubs) layer, as well as negatively impacting mouse populations, both of which will have indirectly affected the tick populations through increased desiccation and a loss of bloodhosts. In more extreme environments, such as in sub-Saharan Africa, tick species have spread from regions of drought to more viable habitats.[54–56] Drought can also impact on pathogen infection rates in ticks. For example, Doby and Bigaignon[57] conducted a consecutive four-year survey (1987–1990) on the level of *I. ricinus* nymphs infected by *B. burgdorferi* in two forests of the western part of France. A decrease in tick infection frequency in one of the two forests was perhaps in connection with a large observed decrease in the micro-mammal populations (but not ticks) due to a drought during 1990.

While few studies have looked into the impact of drought on ticks, evidence has shown that a majority of tick species are reliant upon soil moisture.[52,58–61] Specifically, Medlock et al.[52] found that higher soil moisture, lower mid-day temperatures, and higher cloud cover favoured questing *I. ricinus*. Therefore, summer droughts which cause low soil moisture and drying of microhabitats can result in a sharp decline in host-seeking activities from which ticks may not recover if the drought is prolonged. More recent work by Medlock et al.[61] has shown that in a woodland ecosystem, woodland management strategies can be employed to reduce surface moisture and humidity (hence forcing a local drought) to reduce tick survival and hence activity. Extended periods of sub-optimal atmospheric moisture have been found to have a negative effect on nymphal *I. scapularis* survival.[62,63] Humidity is a major factor in tick ecology and its effect might impact tick-borne disease incidence in humans. Drought is likely to affect tick activity and change the diurnal (night-time) and seasonal (summer aestivation) patterns of activity. A very dry soil and leaf litter layer will increase mortality rates in quiescent *I. ricinus*. Furthermore, the frequency of contact between humans and ticks is the common determinant of any temporal variation in human infection rates by these tick-borne pathogens.[3] Studies from Eastern Europe have shown an increase in outdoor activities as a consequence of increased wealth since the decline of Communism; a decline in industry has changed the amount of local solar radiation, adapting the local climate, thus favouring co-incident seasonality of tick stages, thus increasing co-feeding transmission, and hence increased exposure to Tick-borne encephalitis virus. Transmission of TBEV through co-feeding of larvae and nymphs has been associated with rapid autumnal cooling, rather than drought. Nevertheless any change in seasonal or diurnal activity of different ticks stages associated with drought will impact on tick-borne transmission cycles in complex ways.

Discussion

Arthropod vectors have an ability to rapidly adapt to local changes in climate and habitat.[3] Drought can have a substantial effect on water table levels, vegetation, and aquatic predators; all factors which influence vector populations. Tick populations are likely to be negatively affected by drought as they are dependent upon high levels of humidity and soil moisture, both of which will be dramatically lowered during a drought. For mosquitoes, the lack of precipitation can affect vector populations at the larval and adult stages, and floodwater mosquitoes have demonstrated several adaptations for survival and development in temporary habitats, especially temporary pools of water created by drought conditions.[64] More significantly however, several species of mosquito can produce drought-resistant eggs that are capable of surviving for several years out of water, with subsequent hatching triggered by environmental factors such as changes in water table levels.[65] Urban mosquitoes are adaptable by nature and are able to exploit habitats created as a response to drought (i.e. water storage containers). This adaptation to container habitats has enabled a global movement of invasive aedine mosquitoes, and the consequent local transmission of tropical viruses in temperate countries.

For the UK, the potential effects of wetland construction on potential mosquito vectors need to be considered. Wetlands can serve as mosquito-friendly habitats if they are inappropriately managed, thereby creating the risk of transmission of mosquito-borne diseases to humans and livestock.[65,66] Constructing wetlands that dry out and flood quickly either following heavy rainfall or as a result of managed high groundwater levels artificially re-creates the drought and re-wetting scenario previously discussed. The resulting lack of predators (following a drought or drying event) and the consequent fast emergence (e.g. *Aedes/Ochlerotatus*) or colonization (e.g. *Culex/Culiseta*) of mosquitoes, presents a risk in the UK initially for mosquito biting nuisance, but also potentially for mosquito-borne infections in the future. Globally, drying followed by re-wetting has been related to WNV, SLEV, malaria, and RVFV outbreaks. Additionally, the abundance of nuisance mosquitoes in both natural and constructed wetlands is a foreseeable effect following a drought and re-wetting event.[67] A body of evidence from research conducted by Public Health England entomologists is now able to assess and quantify this impact and guide recommendations for mitigating the potential problems of nuisance and disease vector populations of mosquitoes.

In order of priority for future research, the impact of wetland drying then re-wetting in relation to the consequent increase in mosquito numbers is of most concern for the UK. The impact that drought can have on future arbovirus transmission (specifically WNV), as well as the potential incursion of non-native *Aedes* mosquito vectors (with the ability to exploit container habitats) should also been seen as immediate concerns for surveillance and research. Developing an evidence base for wetland management is a crucial aspect in preparing for the emergence of mosquito-borne disease in the UK, and in aiding and informing policy makers associated with wetland expansion on mosquito nuisance and disease risk. There needs to be a balance between management strategies in order to sustain both wetland biodiversity and human health. It is crucial that interventions are developed and research conducted now to mitigate a future potential mosquito-borne outbreak or indeed the establishment of invasive mosquito species in the UK. A key element of this will be ensuring that both the environmental and public health sectors have the necessary preparedness to respond to such scenarios. This will be increasingly challenging given the increasing pressure on local authorities to reduce spending on pest control, with fewer authorities now directly engaged in mosquito control.[68] This process can be readily enacted through updating national and local ready-made public health and environmental health plans and guidance for an invasive mosquito problem or arthropod-borne outbreak. Vectors and vector-borne diseases are not solely a public health, veterinary, or environmental issue but rather a combination; therefore, close cross governmental working is important to ensure joined up policy is carried through into action.

Limitations and risk of bias

The studies included in this review were limited from the year 1990 onwards. The authors believed that identifying and highlighting recent studies would prove most beneficial to decision makers using this review. Limiting the search to period from 1990 onwards is likely to identify all but the very small minority of systematic reviews conducted before then. Furthermore, not much work was performed on the impact of drought on vector systems before 1990. Additionally, this review did not address temperature as an exposure variable. The combination of temperature and precipitation and their complicated relationship with vectors deserves further attention.

The studies included in this review varied widely in study designs (from observational to experimental) and levels of quality. Quantitative statistics summarizing the studies was not possible due to the varied nature of the study designs and outcomes. A formal assessment of bias was not possible for each individual study. Furthermore, it is difficult to attribute an impact on vectors and vector-borne diseases solely to a drought event, and this issue may be under-investigated and under-reported.

Conclusions and further research

Overall, the literature demonstrated that drought can change key vector habitats by concentrating water into small pools, severely reducing or eliminating predators and competitors, bringing mosquitoes and vertebrate hosts into increasing contact, and forcing mosquitoes to retain eggs or produce drought-resistant eggs. Furthermore, human adaptation to drought particularly through the provision of water storage containers in urban environments and changes in land use all play a role in the changing the risk of future vector-borne diseases. Recommendations for follow-up work include:

- further field research on how hydrological changes (i.e. the drying and re-wetting scenario during/following a drought) may impact different mosquito species;
- further research to investigate what types of wetlands are to be created in the UK, and what significance and impact the different aquatic habitats may have on existing mosquito species and how these will respond to drought;
- identifying environmentally-sensitive wetland management strategies to mitigate nuisance mosquito species and potential pathogen transmission during a drought event;
- inclusion of a vector component in the health chapter of all environmental impact assessments. This applies to newly created habitats (principally wetlands) as well as for habitat management strategies in the event of outbreaks, with strategies for dealing with mosquito nuisance following unnatural drying of aquatic habitats;
- work to better understand the role of winter water storage reservoirs (employed to mitigate the effects of drought) in supporting mosquito populations; and
- identifying evidence-based public health interventions that can be implemented in response to an invasive mosquito problem or arthropod-borne disease outbreak

Author statements

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Competing interests

None declared.

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