REVIEW ARTICLE

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Impact of climate change on the epidemiology of tick-borne encephalitis in Europe – a narrative review

Wpływ zmian klimatu na epidemiologię kleszczowego zapalenia mózgu w Europie: przegląd narracyjny

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Abstract

Introduction and Objective. Tick-borne encephalitis (TBE) is an important viral infection caused by Flavivirus, primarily transmitted by *Ixodes ricinus* ticks. Its incidence and geographic range are increasing across Europe. The aim of the review is to assess currently available evidence on the dynamics of climate change and TBE epidemiology, following a One Health perspective that considers vectors, hosts, environment, and human behaviour. Particular attention is paid to the situation in Poland.

Brief description of the state of knowledge. Rising temperatures are prolonging cumulative growing degree days (GDD), leading to acceleration of tick development and extension of questing seasons. Milder winters reduce tick mortality during diapause, while saturation deficit mediates regional desiccation risk. The most crucial mechanism for amplification is non-viremic co-feeding transmission. This process explains how infected nymphs transmit TBEV locally to larvae on the same host. It is also sensitive to temperature-driven synchrony between tick life stages. Taken together, these factors have led to expansion of *Ixodes Ricinus* to higher latitudes and altitudes, as well as introducing new endemic foci. The national incidence in Poland has risen from 265 cases in 2019 to 805 in 2024, while the vaccination rate remains at a low level. Use of machine learning-based risk models that help identifying emerging hotspots, as well as cost-effectiveness analysis, support vaccination, even below the WHO incidence threshold.

Summary. Although a major but not the sole driver of TBE is climate change, it is necessary to also consider the contribution of human behaviour, land use and host ecology. Current priorities for prevention of further expansion include expanding vaccination coverage, strengthening integrated surveillance, and deploying climate-informed predictive mapping across Europe.

Key words

climate change, tick-borne encephalitis, *Ixodes ricinus*, predictive modelling, One Health, co-feeding transmission

Streszczenie

Wprowadzenie i cel pracy. Kleszczowe zapalenie mózgu (KZM) to choroba wirusowa wywoływana przez Flawiwirusy, przenoszona głównie przez kleszcze z gatunku *Ixodes ricinus*. W Europie rośnie zapadalność na tę chorobę i jej zasięg geograficzny. Celem pracy jest ocena dowodów dotyczących wpływu zmian klimatu na epidemiologię KZM w ujęciu One Health, biorącym pod uwagę wektory, żywicieli, środowisko oraz ludzkie zachowania. Szczególną uwagę zwrócono na sytuację w Polsce.

Opis stanu wiedzy. Wzrost temperatur przedłuża sumę temperatur efektywnych, przyśpieszając rozwój kleszczy oraz wydłużając ich aktywność. Łagodniejsze zimy zmniejszają śmiertelność kleszczy podczas diapauzy, a deficyt wilgotności wpływa na regionalne ryzyko ich wysychania. Najważniejszym mechanizmem amplifikacji wirusa jest niewiremiczna transmisja podczas współżerowania. Proces ten opisuje przenoszenie wirusa przez zakażone nimfy do larw na tym samym żywicielu. Zależy także od synchronizacji stadiów rozwojowych kleszczy, kształtowanej przez temperaturę. Łącznie czynniki te sprzyjają ekspansji zasięgu *Ixodes ricinus* na wyższe szerokości i wysokości geograficzne, jak i do powstawania nowych ognisk endemicznych. Zachorowalność w Polsce wzrosła z 265 przypadków w 2019 roku do 805 w 2024 roku, przy utrzymującej się niskiej wyszczepialności. Modele ryzyka oparte na uczeniu maszynowym, pomagające identyfikować nowe ogniska oraz analizy efektywności kosztowej, potwierdzają zasadność

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szczepień nawet przy zapadalności poniżej progu WHO.
Podsumowanie. Zmiana klimatu jest istotnym, lecz nie jedynym czynnikiem napędzającym KZM, należy bowiem uwzględnić również ludzkie zachowania, użytkowanie gruntów i ekologię żywicieli. Obecne priorytety zapobiegania ekspansji kleszczowego zapalenia mózgu to wzrost wyszczepialności, wzmocnienie zintegrowanego nadzoru oraz wdrażanie map predykcyjnych uwzględniających dane klimatyczne w skali Europy.

Słowa kluczowe
zmiany klimatu, *Ixodes ricinus*, kleszczowe zapalenie mózgu, One Health, transmisja przez współżerowanie, modelowanie predykcyjne

INTRODUCTION

Tick-borne encephalitis virus (TBEV) is a Flavivirus responsible for causing tick-borne encephalitis (TBE). Manifestations of TBE can range from fever, meningitis, to more serious neurological complications such as encephalitis. The endemic areas affected with TBE are historically located in Central/Eastern Europe and parts of Asia. Transmission involves ticks (mainly Ixodes ricinus in Europe) and small vertebrate hosts, such as rodents and shrews [1]. Humans are incidental hosts who become infected when bitten by an infected tick.

In recent years, both TBE incidence and endemic areas have expanded. Reports from across Europe show a sharp increase in the number of cases in Lithuania, Germany, and Sweden. Notably, TBEV has recently emerged in The Netherlands, with the first reported human case occurring in 2016, as well as in the United Kingdom, where the first confirmed local case was noted in 2022 [2]. This raises concerns about the underlying drivers of the disease. Climate change is one of the most important factors, as ticks are strongly dependent on the ambient temperature, resulting in shifts in temperature and humidity having a direct effect on their survival and behaviour [3].

The epidemiological situation in Poland is heterogeneous. TBE is largely associated with Podlaskie and Warmińsko-Mazurskie provinces. Historically, TBE incidence in Poland has been low – 0.3/100 000 in 2020, but in recent years an increase in cases has been noted – 661 cases in 2023 and 805 in 2024. Reported annual vaccine uptake, however, has remained low -0.2% in 2019), but this should not be described as population-level vaccination coverage unless such exact percentage is directly reported [4, 5]. Taken together, these observations indicate the potential for a wider geographic distribution of TBE risk.

OBJECTIVE

The aim of this narrative review is to examine how climate change affects the epidemiology and geographic distribution of TBE in Europe, with particular attention to Poland, and to discuss the ecological, behavioural, and public health factors that modify this relationship. The review focuses on temperature, growing degree days (GDD), winter survival, humidity, co-feeding transmission, host dynamics, and human exposure. It also considers predictive modelling, risk mapping, vaccination economics, and prevention from a One Health perspective.

REVIEW METHODS

A literature review was conducted using searches in PubMed and Google Scholar, supplemented by materials found on official institutional websites and in databases, including those of the World Health Organization, the European Centre for Disease Prevention and Control, the UK Health Security Agency, the National Institute for Public Health and the Environment, the National Institute of Public Health NIH – National Research Institute, and the Chief Sanitary Inspectorate. Publications and official reports issued between January 2011 – April 2026 were included in the review. The literature search was last updated in April 2026. Undated institutional webpages were included when they provided relevant official epidemiological or public health information and were available at the time of the final search update. The search was performed using terms such as ‘tick-borne encephalitis climate’, ‘Ixodes ricinus diapause’, ‘co-feeding transmission TBE’, ‘growing degree days ticks’, and ‘TBE Poland vaccination’. Both observational studies (field data on ticks and hosts) and modelling studies (statistical and mechanistic) were included. References to older foundational work were made where necessary as background information. Preference was given to primary research and official data. Information was extracted on climate mechanisms (temperature limits, GDD effects, saturation deficit impacts), tick life-cycle changes, TBEV transmission (especially co-feeding dynamics), and epidemiological trends. Polish-specific data were sought: NIZP-PZH surveillance bulletins and GIS summaries provided case numbers and vaccination data; official epidemiological and policy information was taken primarily from ECDC, NIZP PZH-PIB/GIS, WHO, UKHSA and RIVM, while peer-reviewed studies were used to interpret mechanisms and predictive models.

Duplicate records, publications without direct relevance to TBE or TBEV, sources unrelated to the European context, non-authoritative opinion pieces, and records providing insufficient information for interpretation, were excluded. Sources were selected according to their relevance, methodological credibility, recency and contribution to the thematic areas addressed in this review. No quantitative meta-analysis was performed.

DESCRIPTION OF THE STATE OF KNOWLEDGE

The following sections summarise current evidence on the epidemiology of TBE in Europe and examines the climatic, ecological, behavioural, and public health factors contributing to changes in its geographic distribution and disease burden.

Epidemiology of tick-borne encephalitis in Europe. In recent decades, an increase in the incidence of tick-borne diseases and an expansion of the geographical range of ticks have been observed [6]. Tick-borne encephalitis (TBE) is a vector-borne viral infection in Europe, with endemic regions stretching from north-eastern France through Central Europe to the Balkans, and from Scandinavia to central Russia. In the European Union/European Economic Area (EU/EEA), 3,650 TBE cases were reported in 2022, corresponding to a notification rate of 0.81 per 100,000 population, which represents a 14% increase compared with 2021 [7]. The disease shows a clear seasonal pattern, with approximately 90% of cases occurring between June and November, with a peak incidence in July. TBE affects men more frequently than women (male-to-female ratio approximately 1.5:1), and the highest incidence is observed in individuals aged 45–64 years [4].

In Poland, TBE remains geographically concentrated in endemic regions, particularly in the north-eastern part of the country. Historically, around 200–300 cases were reported annually in Poland, but this pattern changed in recent years: 265 cases were recorded in 2019, 446 in 2022, 661 in 2023, and 805 in 2024. In 2024, the highest incidence was observed in the Podlaskie and Warmińsko-Mazurskie provinces [5]. A broader rise in TBE burden has also been documented across Europe [7, 8, 9]. The epidemiology of TBE in Poland was also affected during the COVID-19 pandemic. According to surveillance data, between 2008 – 2020, 3,016 TBE cases were reported in Poland compared with 3,620 hospitalisations, with the largest discrepancy in the first pandemic year. Although surveillance data suggested a decrease in reported cases, hospitalisation data indicated a simultaneous increase, suggesting potential under-reporting due to reduced access to specialised diagnostics [4]. In contrast to Poland, several European countries reported an increase in TBE cases during the pandemic [10, 11, 12]. Long-term observations indicate that the case fatality rate in Poland remained relatively low, typically below 2%, with an average of around 1% [8].

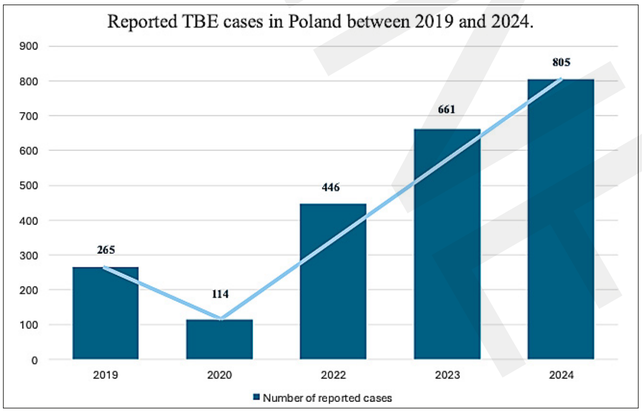

Figure 1. Reported TBE cases in Poland, 2019–2024 [4,5]

Factors influencing the epidemiology of tick-borne encephalitis. The increase in TBE incidence is multifactorial, with the expansion of tick habitats being influenced by environmental, climatic changes, and by human impacts on ecosystems. These factors also affect virus circulation among ticks and reservoir animals, thereby affecting the risk of human infection [13, 14]. The likelihood of tick bites is increased by occupational exposure and affecting those engaging in outdoor recreation, and spending time in forested or green areas. Nowadays, leisure activities in natural settings are becoming more popular, particularly after the easing of COVID-19 restrictions, which leads to increased exposure to infected ticks [13].

Recent agricultural trends in livestock farming have also contributed to increased interactions between ticks, domestic animals, and humans, which has increased the chances of infections caused by tick-borne diseases [14]. TBE occurrence could be variable among different demographic groups and in correlation with the intensity of exposure to tick habitats. Foresters and farmers, among others, working in the open air are especially prone to infection by tick-borne diseases. Research shows that the risk of disease is more likely among these individuals due to the frequency of tick bites and insufficient protection against the risks [15].

Climate drivers of tick ecology. Climate plays a crucial role in the life of ticks, affecting developmental processes, their viability, level of activity, and distribution over the territory. The metabolism of the Ixodes ricinus ticks depends to a high degree on the surrounding temperature levels; thus, temperature is a key element for the development of these ticks. The activities related to searching for a host by the Ixodes ricinus are heavily influenced by both temperature and humidity conditions; for instance, warm springs can accelerate seasonal behaviours [3, 16]. Higher spring temperatures significantly affect the emergence process of the ticks. High summer temperatures lead to a rise in GDDs, which speeds up their development. Mechanistic modelling from Hungary suggests that warming can shorten the tick life cycle, extend questing seasons and increase the abundance of susceptible larval and nymphal stages, thereby increasing transmission potential [1]. Additionally, in line with these findings, projections suggest that the climate warming in Hungary is expected to lead to higher tick densities, and the expansion of TBEV transmission (R_0), mainly due to faster tick development [1].

As temperatures continue to rise, ticks are expanding their geographic range northward and into higher altitudes, where previously low temperatures limited their development and overwinter survival [17]. This allowed Ixodes ricinus to reach elevations up to 1560 m a.s.l. and expand into northern latitudes, particularly in Scandinavia [8, 18].

Apart from temperature during active seasons, winter conditions also play an important role. Historically, the presence of cold winters limited the geographic spread of the ticks. Ixodes ricinus is adapted to withstand sub-zero temperatures, particularly when sheltered under leaf litter [19], whereas milder winters reduce mortality of ticks while they are in the state of diapause. However, laboratory studies show that survival declines markedly below –5 °C in open air, while insulation by leaf litter or snow can improve overwintering success [8]. According to climate modelling, low levels of snowfall in north-eastern Poland can cause exposure to even colder temperatures. Warm winters increase chances for survival, hence leading to increased populations in springtime [16].

Besides temperature, humidity is another key environmental factor affecting tick survival. Humid conditions are required for ticks' survival, as dry and hot air (high saturation deficit) increases their risk of drying out. Impacts of climate change vary by region; for example, models in Central Europe showed that tick survival and activity decrease sharply when saturation deficit (SD) exceeds about 5–6 mmHg [3]. Higher temperatures during summer can contribute to increased

SD, but forested areas such as northern Poland and the Baltics region, often retain higher humidity resulting in reduced risk of desiccation. Moderate climate warming with maintained humidity results in increased tick activity, while extremely dry climates inhibit activity. These changes also translate into shifts in tick phenology. Global warming leads to earlier spring activity and prolonged autumn activity of ticks, as higher temperatures accelerate development rates and extend the seasonal window of activity [17]. These shifts increase the duration of host-tick contact because warmer conditions allow ticks to remain active later in the year, and resume activity earlier after winter dormancy [17, 20].

Long-term monitoring indicates nymph questing begins earlier than before. In Poland, however, phenological data is limited. Milder conditions may extend seasonal tick activity and advance spring onset, although the magnitude of these shifts is context dependent [16], which implies earlier tick emergence. Correspondingly, extended duration of mild autumns elongates tick activity into October.

Overall, climate-driven changes in temperature, humidity, and seasonality interact to shape tick population dynamics and risk of TBE development. In addition to temperature, humidity and desiccation risk remain critical constraints on tick survival and host-seeking activity [16].

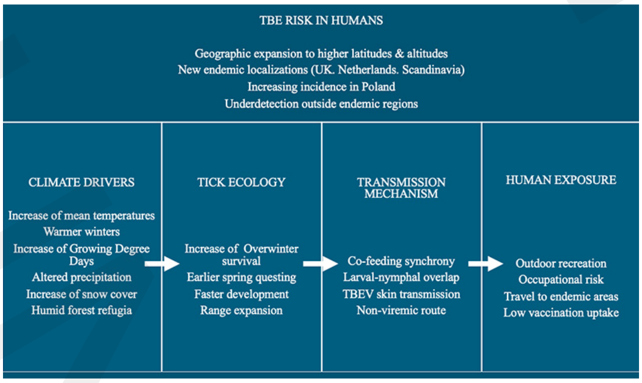

Figure 2. Climate change pathways influencing TBE risk in humans

Co-feeding transmission of TBEV. TBEV persistence depends largely on non-viremic co-feeding transmission, where infected nymphs transmit the virus to larvae feeding nearby on the same host, but without leading to systemic infection of the host [1]. Specifically, this process is located within the skin, as the virus is transmitted between the saliva of nearby feeding ticks [1, 3]. The main reservoir hosts, such as rodents (e.g., Apodemus mice), typically develop only short-term low-level viraemia [21]. Consequently, this level is not sufficient for transmission through the bloodstream, and the hosts do not suffer from the symptoms of TBEV. Field, experimental and modelling studies support co-feeding as a key natural mechanism maintaining TBEV in endemic foci [1]. This mechanism of transmission is commonly observed in spring, when larvae feed on small mammals shortly before transformation into nymphs [3].

Furthermore, research has suggested that early increase of temperatures to about 10 °C during spring, or in contrast, a rapid cooling in autumn, could be the factor extending the period when these stages overlap [3]. Despite these proposed mechanisms, it is important to note that empirical data is mixed. A study conducted in Germany between 2009 – 2018, found no clear link between spring temperature patterns and tick infection rates; however it was shown that larger populations of nymphs were associated with an increased rate in cases of human infection [3]. On the contrary, a study from Italy stated that lower temperatures in the autumn of the previous year were associated with a higher number of co-feeding ticks on mice during spring, suggesting that autumn weather and host conditions may impact tick dynamics in the following year [22]. Overall, current evidence supports the central role of co-feeding transmission in TBEV ecology, although the relative contribution of climatic and ecological factors influencing this process remains to be fully clarified.

Host dynamics and human exposure. Changes in land use and wildlife dynamics are another group of factors influencing TBE cycles. In many regions, reforestation and suburban development have led to the expansion of tick-favouring habitats [23]. Large mammals, such as deer, support amplification of the tick population, whereas small mammals, like wood mice, are directly involved in the sustained transmission of TBEV. In comparison, land conversion for agriculture purposes, may locally reduce suitable tick habitat [11]. Host-related effects also shift dynamically, as changes in rodent abundance and co-feeding patterns can alter the local TBE hazard from year-to-year [22].

Beyond ecological factors, changes in human behaviour due to climate change also play a significant role in TBE dynamics. Warmer weather encourages outdoor activities – hiking, camping, berry picking – meaning that humans tend to spend more time outside. Surveys showed that a substantial proportion of Europeans (e.g. 39% of EU residents in 2022) travel to or spend time in TBE-endemic areas [8]. This is consistent with higher rates of non- occupational exposures. Awareness of tick-related risks also varies across populations. In Poland, for example, although vaccination uptake has increased, it remains insufficient in most affected regions, which may reflect gaps in health communication [24]. Importantly, periods of human outdoor activities often overlap with peak tick activity in spring and summer. Mild autumns prolong both human outdoor activity and tick activity, leading to extension of the period in which human-tick encounters may occur.

Notably, independently of climate, lifestyle changes have also contributed to the higher incidence of TBE. The end of the Cold War led to broader socio-economic changes, while today climate now amplifies or triggers new trends. Risk increases when environmental and human factors come into alignment' as exemplified by an unusually warm spring (climate) favouring the questing of ticks, while at the same time, people are more likely to spend time outside (behaviour), resulting in a spike in cases [8, 11, 20]. Collectively, these interactions emphasize that TBE risk is shaped by the combined effects of environmental and behavioural factors, potentially intensifying further under changing climatic conditions.

Predictive modelling and risk mapping. Management of the spread of TBE is increasingly supported by advances in predictive modelling and risk mapping. Spatial modelling approaches are increasingly used to predict and control cases of infection [25]. These models use machine learning (ML) and incorporate multiple factors, such as climate, land cover and host data, to predict the spread of TBEV [26]. For example, Kelly et al. used boosted trees and MaxEnt models

Table 1. Key studies analyzing and predicting the impact of climate on TBE dynamics

Reference	Country of the research	Study Type	Key variables	Key findings	TBE-climate connection relevance
Nah et al. [1]	Hungary	Mechanistic modelling	Temperature, growing degree days , tick life cycle	Climate warming increases TBEV transmission, by lengthening tick activity seasons and increasing larval–nymphal overlap	Climate influences tick feeding synchrony, which can amplify TBEV transmission.
Borde et al. [3]	Germany	Field monitoring	Spring temperature, tick infection rates, saturation deficit, density of nymphs, days with rainfall	Spring temperature is not clearly linked to infection, but greater nymph abundance correlates with more human cases	Climate and TBE transmission connection is complex and cannot be captured by simple linear models.
Rosa et al. [22]	Italy	Field study	Autumn temperature, rodent density, co-feeding rates	Lower temperatures in the previous Autumn and higher host density predicted increased co-feeding overlap the following spring.	Climate has delayed effects on tick–host interactions, jointly determining annual TBE risk.

based on confirmed TBEV occurrence points across Europe [27]. Their model identified known hotspots in Central Europe and the Baltic countries, as well as flagged new areas with high suitability – Western Norway, northern Denmark, north-eastern Croatia, eastern France, and northern Italy [27]. Another approach to assess the risk of human infection cases is a model by Dagostin et al. which integrated ecological hazard (tick habitat) with human exposure. Predictions of the model include rising TBE risk in north-western and south-western Europe, and generated year-ahead risk maps that can be used for targeted prevention [28]. Collectively, all these models demonstrate the importance of the climate (temperature, precipitation), land cover (forest, vegetation indices) and host/usage variables as key predictors.

In addition to modelling approaches, satellite data is increasingly used to refine risk estimates. Vegetation indices and climate anomalies can be used to support early warning systems for tick activity [29]. Risk mapping is being used more frequently, especially in travel medicine and by local health agencies to guide vaccination and preventive measures [30].

Despite recent progress, surveillance gaps remain and many areas predicted to be at high risk lack systematic monitoring of tick and human interactions. The emergence of TBEV in previously unaffected countries implies that many silent foci may exist undetected. Enhancing tick surveillance by testing ticks for TBEV and conducting serological surveys in rodents and humans is essential for improving early detection and guiding targeted public health interventions.

Public health implications and vaccination economics. Effective inactivated TBE vaccines are available, and vaccination is the most effective preventive measure in endemic regions such as Austria [31]. Many other European countries also have systematic recommendations, although they can vary by region even in the same country, depending on the risk of infection [32, 8]. In Poland, for example, vaccination is highly encouraged only for the residents of and travellers to the endemic Podlaskie, Warmińsko-Mazurskie and Kujawsko-Pomorskie provinces) [4, 24].

Vaccination provides high levels of protection, with efficacy exceeding 95% after completion of the primary schedule [31, 33]. In Poland, two licensed vaccines containing inactivated TBE virus are available in formulations for both adults and children older than one year of age. The standard immunisation schedule consists of three primary doses, followed by a booster after three years, and further doses every 3–5 years. An accelerated schedule is also available that can be used in peak tick season, or for last-minute travellers [14, 34]. In countries with high vaccination coverage, such as Austria where rates exceed 80%, it is observed that immunisation can substantially reduce the incidence of TBE.

Immunisation policies are being re-evaluated as TBE continues to spread. Some countries in Europe are lowering the incidence threshold and publicly funding these programmes, an approach that is supported by cost-effectiveness analyses. A recent German study has shown that the vaccination of older adults (age group: 60–85 years) is economically justified even when incidence is below the WHO threshold (5 cases per 100,000 population) [35]. Therefore, expansion of target groups, including children, in endemic fringe zones, has been proposed.

Alongside vaccination, the broader economic impact of TBE should also be considered. Consequences of infection can lead to long-term disability, including neurological sequelae, such as tremors, ataxia, sensory disturbances, and cranial or spinal nerve damage [36]. Hospitalization when treating this disease is common and, in some cases, even intensive care may be required. Indirect costs, such as lost productivity and caregiving, are substantial. It is suggested by modelling studies that in some settings, even moderate vaccination costs can be offset by the reduction in disease burden.

Prevention of TBE is based on a combination of vector control, personal protective measures, and immunisation. Personal protection includes wearing clothing that covers the skin, using repellents such as DEET (N,N-diethyl-meta-toluamide), and removing ticks as soon as possible after a bite. Another important component is education of the public, which should be aimed at increasing awareness of tick exposure and protective behaviours [13]. The content of these messages should be adapted according to changing risk maps. Patients considered at high-risk, should be counselled on TBE prevention by primary care physicians and travel clinics, particularly in formerly non-endemic regions. Educational materials should also mention alimentary transmission, as TBE can be acquired through contaminated unpasteurised dairy products [37].

Synthesis of evidence and knowledge gaps. The evidence reviewed indicates that climate change is an important driver of the changing epidemiology of TBE in Europe, although it is not the sole determinant. By affecting tick development, survival, seasonal activity, and geographic distribution, climatic changes contribute to the expansion of the tick populations and longer periods of potential transmission [1]. These effects interact with the use of land, wildlife dynamics, and human behaviour. Models and field studies consistently indicate that these ecological shifts raise the risk of TBEV spread into areas that are now considered low risk [1, 27]. In particular, the co-feeding mechanism leads to a strong non-linear response to climate change. Surges in TBEV transmission can be caused by sudden warming, whereas a more gradual change in temperatures may reduce this effect [1, 3]. Simpler models often overlook this aspect, which highlights the importance of understanding the underlying mechanisms.

It is not only climate that leads to these shifts in epidemiology, fundamental factors include land-use, wildlife management and human behaviour. In Poland, reported TBE incidence remains geographically concentrated despite broad environmental suitability. Available evidence suggests under-detection outside typical endemic areas [4], with surveillance gaps remaining. One study found substantial under-reporting of TBE in Poland [4]. Without improved diagnostics and reporting, the effects of climate may be difficult to determine nevertheless, correlations between climate anomalies and TBE spikes have been observed in many countries, suggesting a genuine climate effect.

TBE is a clear example of a One Health issue. Climate is affecting wildlife hosts and tick vectors, which consequently influence human risk of infection; therefore, there is a need for coordinated monitoring across veterinary, entomological, and public health sectors.

Limitations of the study. Several limitations of this review should be acknowledged. As this was a narrative rather than a systematic review, study selection was not based on a formal risk-of-bias assessment. Evidence from regional climate models was sometimes extrapolated to Poland because country-specific data, including precise growing degree day estimates, were limited. The included studies differed in their design, geographic scale, climatic variables, and outcome definitions, which limits direct comparisons. No original or proprietary datasets were analysed.

There are also important data limitations. Numerous models rely on broad climate variables and assume that ticks are responding in the same way across different environments, but without consideration of local conditions such as soil moisture and plant diversity. Another aspect is lack of sufficient long-term field study research, examining how different tick stages overlap under changing weather conditions. The same applies to data on human behaviour, such as travel and outdoor activities.

These limitations are particularly evident in countries such as Poland, where the situation is even more limited than in other European countries in terms of data availability. There are insufficient studies linking climate metrics to tick or TBE data. The main limitation in Poland is not the existence of climate-related studies as such, but the availability of long-term national analyses integrating climatic indices, tick data and human TBE surveillance. Surveys about tick infections have not been extensively performed outside known foci.

Public health systems must adapt to changing conditions. Actions to increase public awareness of TBE in newly at-risk regions, updating diagnostic approaches, and revising vaccination guidelines, must be taken. Climate projections should also be taken into account for updating immunisation strategies, as areas currently below traditional incidence thresholds may soon become areas at higher risk. This supports earlier intervention, as shown by cost-effectiveness studies [35].

Furthermore, using forecasts of unusually warm springs for implementing early-season warnings could facilitate more targeted prevention efforts, including more frequent tick checks, use of repellents, and focused protection for at-risk groups.

In Poland, several measures may be particularly relevant as TBE remains a concern for public health. There is a need for updating vaccination recommendations, including subsidising vaccines in areas where risk is increasing, particularly for older adults [35].

Another area for improvement is monitoring. This could be achieved by correlating data on ticks and human cases. Clinicians should consider testing for TBEV, when treating patients with neurological symptoms during tick season. Development of a national early warning system based on climate data, would be beneficial. Such a system could improve the prediction of early onset of warm springs, alert both the public and healthcare services, and enhance the capacity to diagnose and manage TBE.

Overall, for effective TBE prevention in a changing environment, integration of climatic, ecological and public health data will be essential.

SUMMARY

The risk of tick-borne encephalitis is increasingly shaped by climate change through both ecological and behavioural factors. A One Health perspective suggests that, without appropriate action, TBE may continue to spread into new areas. Combining research on climate-tick interactions and anticipatory public health measures is necessary for risk reduction. Expanding vaccine coverage, strengthening cross-sector monitoring, and using predictive climate models, should be priorities for prevention. However, important challenges remain, such as gaps in data and model limitations. Addressing these challenges will require the implementation of evidence-based measures.

Several research gaps also remain, leaving a need for more experimental studies that focus on tick co-feeding under different climate conditions, as well as the development of climate-driven predictive models for TBE spread in Poland, and in other European countries. Surveillance is another area that requires strengthening, especially in areas where new risks are expected. Combining tick monitoring and human serological studies is crucial. Integrated surveillance systems that link entomological, wildlife, and public health data need to be strengthened. Moreover, implementing climate-informed warning systems, along with targeted public education campaigns is another idea for reducing future risk.

These research priorities should be supported by targeted policy actions, including lowering the threshold of vaccination recommendations, particularly for older adults in newly affected regions, or people who tend to spend most of their time outside.

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