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Review Article

Hard ticks and tick-borne pathogens in Mongolia—A review

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ABSTRACT

Ticks and tick-borne pathogens (TBPs) pose a considerable threat to human and animal health in Mongolia; a large and sparsely inhabited country whose economy is largely dependent on animal production. Intensive contact between herdsmen and their livestock, together with the use of pastures without fencing, allows contact between wildlife, domestic animals and humans, thus creating ideal conditions for epizoonoses and zoonoses. Consequently, ticks and TBPs cause significant medical, veterinary, and economical concern. This review summarizes the current state of knowledge about this zoonotic problem in Mongolia, focusing on tick species from the genera *Ixodes*, *Haemaphysalis*, *Dermacentor*, *Hyalomma*, and *Rhipicephalus*, which are associated with particular vegetation zones of the country. The most important tick species of medical and veterinary concern are *Ixodes persulcatus* and *Dermacentor nuttalli*, which are found in northern boreal forests and central steppes, respectively. These tick species transmit a wide variety of TBPs, including tick-borne encephalitis virus, *Borrelia*, *Anaplasma*, and *Rickettsia* bacteria, and *Babesia* parasites infecting rodents, wild ungulates, livestock, and humans. Despite basic characteristics of the biology of ticks and TBPs in Mongolia being known, further research is needed to gain more precise and quantitative data on what tick species and TBPs are currently present within Mongolia, and their effects on human health and animal production.

1. Introduction

Mongolia is a large, sparsely populated, rural country covering a total area of 1.5 million km^2 with a total human population of approximately 3 million. Many Mongolians practice a traditional nomadic pastoral way of life and thus the total number of livestock in Mongolia is estimated to be about 30 million sheep, 27 million goats, 4.4 million cattle, 4 million horses, and 434,000 camels (NSOM, 2017). Intensive contact between livestock and their herdsmen creates ideal conditions for the transfer of pathogens associated with various epizootic and zoonotic diseases, particularly via ticks. As a result, ticks and tick-borne pathogens (TBPs) cause substantial economical, veterinary, and medical problems in Mongolia. The distribution of ticks and TBPs in Mongolia is broadly related to local climatic conditions, which are considered to be mostly arid. Mongolia is a landlocked country located in central-east Asia between Russia and China, characterized by long, cold winters, during which night temperatures can drop to −40 °C. The average precipitation is highest in the north (200–350 mm/year) and lowest in the south (100–200 mm/year; Farukh et al., 2009). These differences in rainfall determine the Mongolian vegetation zones, dividing Mongolia into Northern boreal forest (taiga), forest-steppe, steppe, semi-desert and desert zones, as one moves further south (Fig. 1). High mountains are typically characterized by alpine tundra (Farukh et al., 2009).

Nomadic pasture with minimal fencing allows frequent contact between livestock and wildlife (Berger et al., 2008), leading to the occurrence and transfer of various disease agents. Examples of such transmission includes the spread of Peste des Petits Ruminants virus from sheep to saiga antelopes (*Saiga tatarica*) in 2017 and subsequent massive mortality of these antelopes (Kock et al., 2018; Shatar et al., 2017), as well as the transfer of the Foot-and-Mouth virus from Mongolian gazelles (*Procapra gutturosa*) to livestock (Bolortsetseg et al., 2012; Nyamsuren et al., 2006). Intensive contact between nomads and their livestock also allows for the spread of many zoonotic disease agents, such as those causing rabies, anthrax and brucellosis (Batsukh et al., 2013; Ebright et al., 2003; Odontsetseg et al., 2005). Furthermore, ticks and TBPs are a very important issue in Mongolian human and veterinary medicine because various hard ticks of the genera

Abbreviations: CCHFV, Crimean-Congo haemorrhagic fever virus; TBPs, tick-borne pathogens; TBEV, tick-borne encephalitis virus; TBRF, tick-borne relapsing fever

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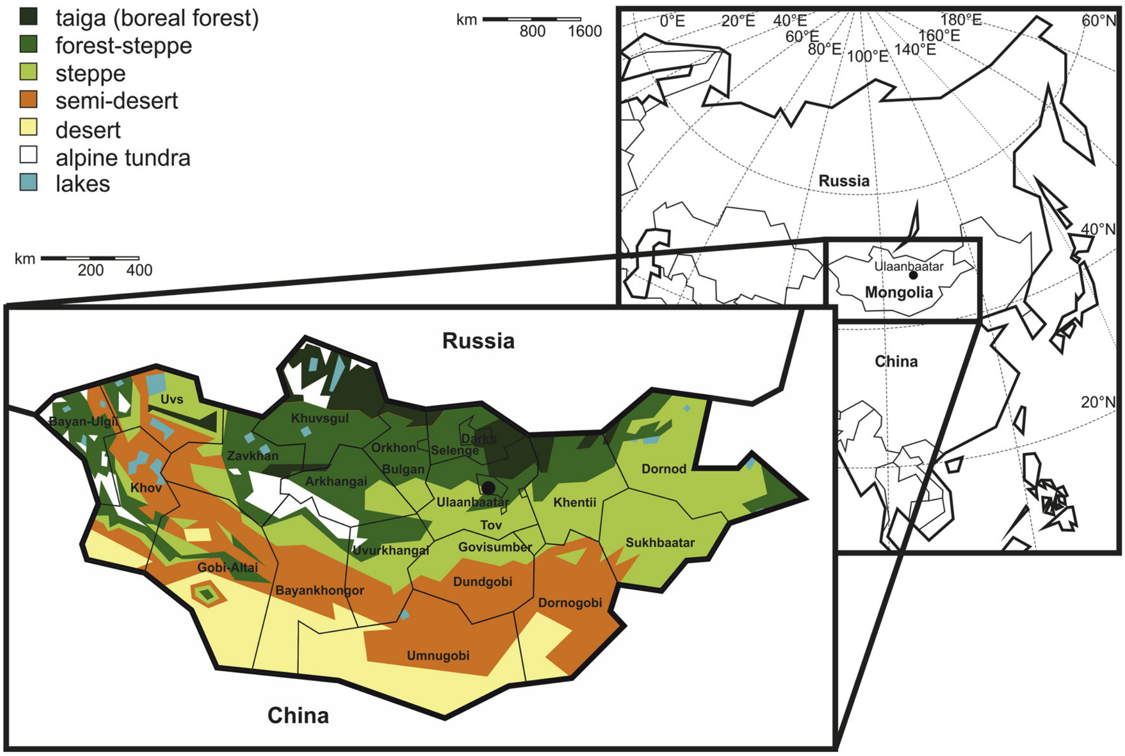

Fig. 1. Geographic and biogeographic divisions of Mongolia: Mongolia is a large landlocked country situated in the central part of eastern Asia between Russia and China. It is divided from north to south into several biogeographical zones: boreal forest (taiga – dark green), forest-steppe (green), steppe (light green), semi-desert (yellow) and desert (orange) zones. High mountains are characterized by alpine tundra (white). Lakes are depicted by blue on the map. The map was prepared based on data from (Farukh et al., 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ixodes, *Haemaphysalis*, *Dermacentor*, *Hyalomma,* and *Rhipicephalus* are found in Mongolia. These ticks are associated with diseases including borreliosis, rickettsiosis, tick-borne encephalitis, and various types of piroplasmosis. However, information regarding TBPs in Mongolia have been published in a variety of languages, including Russian, German, and Mongolian, as well as within various sources, such as public and veterinary health reports. Therefore, this review aims to summarize this information into the English language and compare it with similar information on ticks and TBPs in Russia and China to highlight the need for further research into this problem within Mongolia.

Preparation of this review was performed using a systematic literature search (using the keywords "Mongolia AND tick") carried out on the electronic databases PubMed and Web of Science (WoS), at the beginning of May 2019. The search included publications in English, Russian, German, and Mongolian. After removing duplicates, relevant articles were selected based on whether they provided information on i) the occurrence of ticks, ii) occurrence and prevalence of TBPs either in any tick or host species, or iii) any information about patients infected by TBPs within the State of Mongolia. Literature cited by the selected research articles were then screened and added to the publication database, if they met the afore-mentioned criteria. In total 63 and 77 articles were found in WoS and PubMed, respectively. Further we removed duplicate articles (48 articles) and articles which did not meet criteria i), ii), and iii) (54 articles), which led to a remaining number of 38 publications for inclusion into the review. A further two articles found outside of PubMed and WoS were added to the literature used to total a final 40 publications. From these 40 articles, information was extracted regarding ticks, TBPs, and their hosts, together with information on the methods used for their detection, the province (aimag) and locality where the samples were collected, and the date when they were collected. The information was subsequently processed into a description of the tick species and their presence within Mongolia (Fig. 2), as well as the incidences of TBPs within the various provinces (Fig. 3). This information is not only necessary to describe the occurrence of ticks and TBPs in Mongolia, but also to summarize the current situation within Mongolia for consideration of implementing potential mitigation strategies for tick populations and TBPs to decrease the burden of zoonotic diseases.

2. Occurrence of hard tick species within Mongolia

Being landlocked, Mongolia shares similar biotopes and climatic conditions with its neighbors, China and Russia. Thus, it is expected that these countries would share similar tick species and TBPs; however, less tick-focused research has been performed within Mongolia compared to its neighboring countries. Nonetheless, it has been shown that the existence of various vegetation zones from boreal forest, to steppes and deserts in Mongolia allows for the existence of many different tick species adapted to completely different biotopes (Dash, 1969). Although ticks from the genera *Ixodes*, *Haemaphysalis*, *Dermacentor*, *Hyalomma*, and *Rhipicephalus* have been reported in Mongolia (Dash, 1969), many representatives of these genera were described only once. Therefore, additional research is needed to improve our understanding of the current tick occurrence in Mongolia. Only *Ixodes persulcatus* and *D. nuttalli* are studied intensively, as they seem to be the two most important species, from a human and animal health perspective.

2.1. Genus Ixodes

Three tick species of the genus *Ixodes* have been reported in Mongolia, namely *I. persulcatus*, *Ixodes crenulatus*, and *Ixodes lividus* (Dash, 1969; Dash et al., 1988). *Ixodes persulcatus* is the most intensively studied species as it is a vector of TBEV as well as human pathogenic *Borrelia*, *Anaplasma* and *Babesia* in Mongolia. This tick has been reported repeatedly in various taiga localities, mainly within the

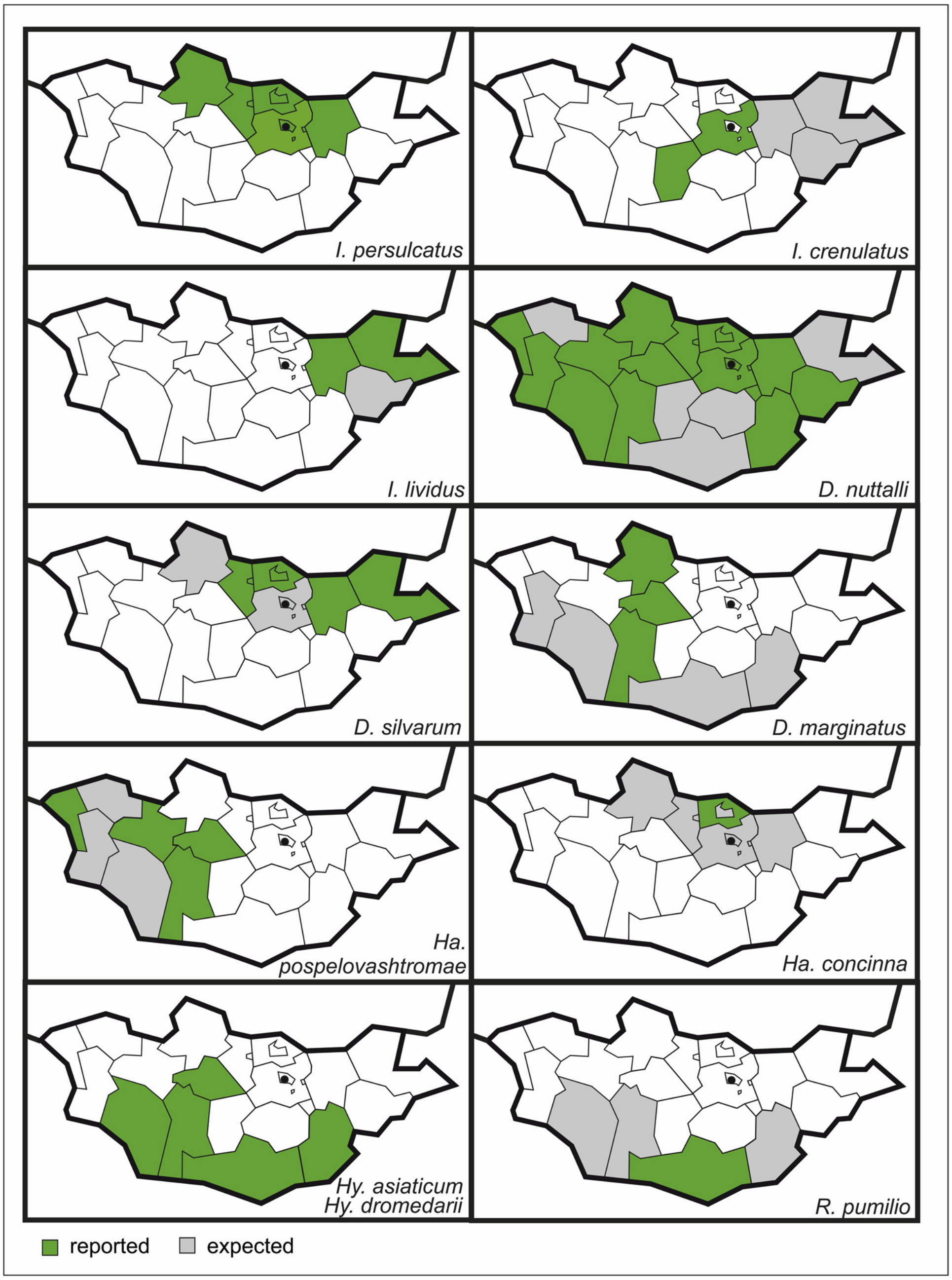

Fig. 2. Distribution of tick species by aimag in Mongolia: Ticks from the genera *Ixodes*, *Haemaphysalis*, *Dermacentor*, *Hyalomma*, and *Rhipicephalus* occur in Mongolia. Ticks adapted to forest ecosystems are usually present in the northern part of Mongolia. Ticks preferring more arid localities live to the south. The absence of reports of some tick species in aimags with otherwise optimal climatic conditions may be caused by lack of collection effort rather than true absence. Therefore, the confirmed aimags where ticks were collected are shown in green and the aimags without collection records but where a tick species is expected to occur based on suitable environment are shown with grey shading. Aimags shown in white lack records of a given tick species and do not contain suitable environments for the tick. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

northern aimags of Khuvsgul, Selenge, Bulgan, and Khentii (Dash, 1969; Iwabu-Itoh et al., 2017). *Ixodes crenulatus* can be found in steppe-covered localities of the northern and central provinces of Mongolia (Uvurkhangai, Tov, and Dornod), where it feeds on rodents (mostly Siberian marmot), small and large carnivores and insectivores (Dash, 1969). In China, but not in Mongolia, *I. crenulatus* was found to transmit agents of tick-borne rickettsioses (Han et al., 2018). *Ixodes lividus* occurs in the north-eastern part of the country. This tick may be found within the nests of bank swallows (*Riparia riparia*) (Dash, 1969). *Ixodes lividus* is known to transmit Kama virus in Russia (Lvov et al., 2014, 1998) and *Rickettsia* in the U.K. (Graham et al., 2010), but no research has been done to detect TBPs in *I. lividus* in Mongolia.

2.2. Genus Dermacentor

Ticks of the genus *Dermacentor* are represented by three species in Mongolia, namely *D. nuttalli*, *Dermacentor silvarum*, and *Dermacentor marginatus* (Dash, 1969; Dash et al., 1988). *Dermacentor nuttalli* is typically found within the xerophilous steppes of northern and central Mongolia (Dash, 1969). The adult *D. nuttalli* females feed mostly on ungulates, while the immature life stages feed on rodents. In Mongolia, *D. nuttalli* was found to be infected with numerous TBPs. *Dermacentor silvarum* (sometimes called *Dermacentor asiaticus* in the Far East region) is found within the taiga forests in northern Mongolia and the forests surrounding the Khentii mountains (Dash, 1969). Similar to *D. nuttalli,* the adult females feed mostly on ungulates and boars, while the immature life stages feed on rodents. *Dermacentor silvarum* is known to be infected with *Rickettsia rauoltii* in Russia and China (Wen et al., 2014; Tian et al., 2012; Han et al., 2018; Cao et al., 2008) but no pathogens were found in *D. silvarum* in Mongolia; however, only six ticks were screened (Narankhajid et al., 2018). *Dermacentor marginatus* (previously referred as *Dermacentor dagestanicus*) was reported several times within the deserts of south-western Mongolia, where it feeds on domestic animals (Dash, 1969). *Dermacentor marginatus* was shown to transmit

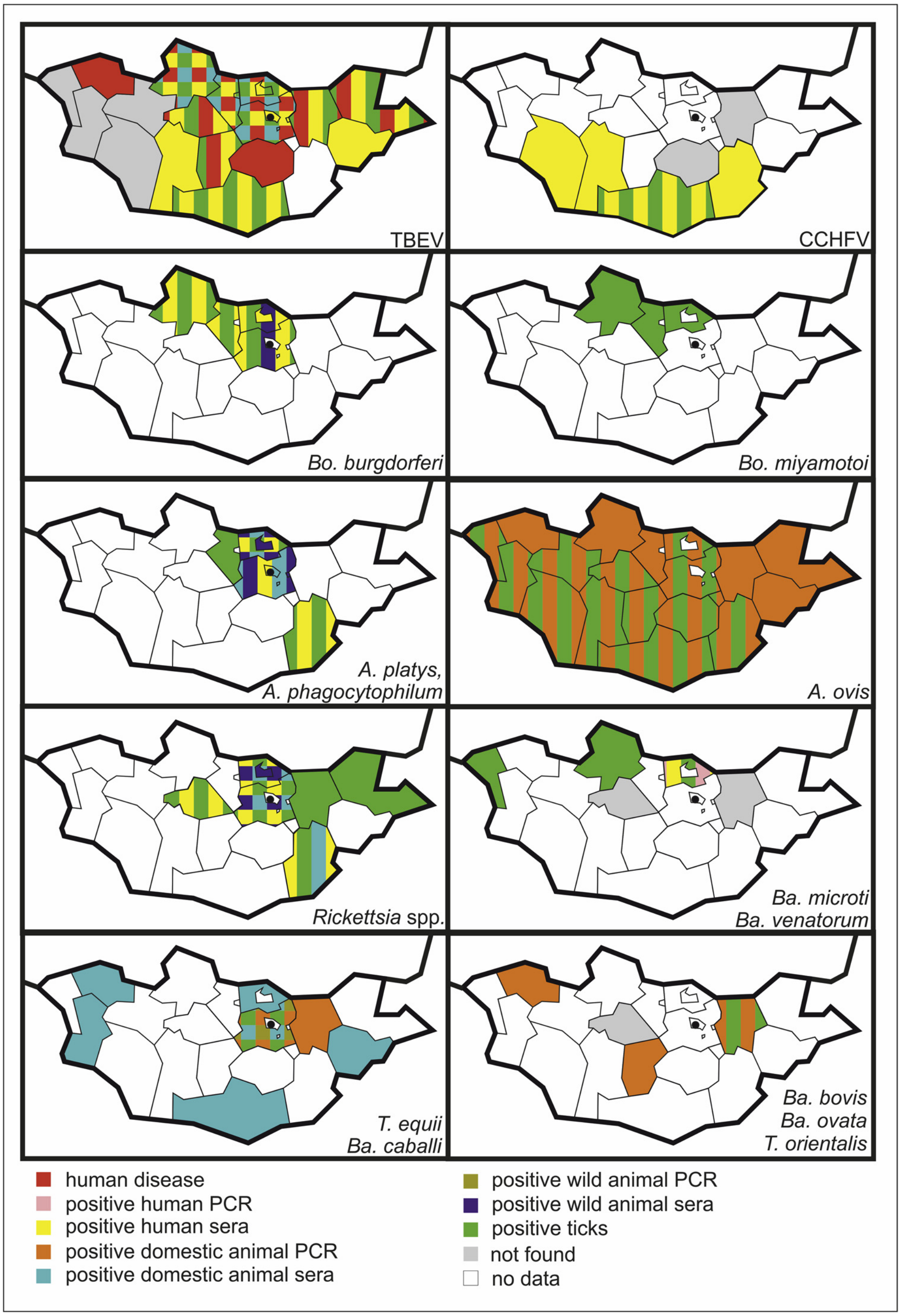

Fig. 3. Distribution of tick-borne pathogens by aimag in Mongolia: Most tick-borne pathogens in Mongolia are transmitted by either *Ixodes persulcatus* or *Dermacentor nuttalli*. Pathogens transmitted by the forest-associated tick *I. persulcatus*, including *Borrelia* spirochetes, are most prevalent in the northern part of Mongolia covered by boreal forest, while pathogens transmitted by the desert tick *Hy. asiaticum* (Crimean-Congo hemorrhagic fever virus) are present in the southern aimags. The absence of tick-borne pathogens in some aimags where both the tick vectors and suitable vertebrate reservoir hosts are present may be caused by lack of data.

Anaplasma phagocytophilum in Mongolia (Narankhajid et al., 2018) and *R. raoultii, Rickettsia sibirica,* and *Rickettsia slovaca* in neighboring parts of China (Song et al., 2018).

2.3. Genus Haemaphysalis

Two species from the genus *Haemaphysalis* have been reported in Mongolia: *Haemaphysalis pospelovashtromae* (Dash, 1969) and *Haemaphysalis concinna* (Danchinova et al., 2007). *Haemaphysalis pospelovashtromae* is typically found in areas of higher elevation, such as the arid steppes in central and western Mongolia. The adults of this species commonly feed on sheep, while larvae and nymphs can be found on rodents, such as ground squirrels, pikas, and voles (Dash, 1969). *Haemaphysalis concinna*, a generalist tick species that infest various mammals and birds, was detected within secondary forest habitats of the Selenge area (Danchinova et al., 2007). These ticks are infected with various TBPs in the Far East including severe fever with thrombocytopenia syndrome virus (Meng et al., 2015), *Borrelia* (Pukhovskaya et al., 2019), *Rickettsia* (Igolkina et al., 2018b), and *Babesia* (Wei et al., 2016). No reports currently exist for TBPs in *Ha. concinna* in Mongolia. Another *Haemaphysalis* species, *Haemaphysalis longicornis*, was reported from the surrounding parts of China, in similar habitats and on host species similar to that what can be found in Mongolia (Li et al., 2014; Rubel et al., 2018). Considering these factors, introduction of this tick into Mongolia may be expected.

Table 1
Morbidity and mortality of selected tick-borne diseases among citizens of Mongolia from 2016 to 2018: Three tick-borne diseases, tick-borne encephalitis (TBE), Lyme borreliosis, and tick-borne rickettsiosis (TBR), are monitored by the local medical authorities in Mongolia. Unfortunately, available data are sparse and even missing for several recent years. Nevertheless, some increase in prevalence of these diseases, but not in the mortality for them, can be observed. Tick-borne diseases likely were undiagnosed, misdiagnosed or under-reported in recent years.

	2016	2017	2018
Morbidity (total number)			
Tick-borne encephalitis	52	62	32
Lyme borreliosis	78	46	24
Rickettsiosis	196	357	203
Morbidity (cases per 10,000 inhabitants)			
Tick-borne encephalitis	0.17	0.20	0.10
Lyme borreliosis	0.26	0.15	0.08
Rickettsiosis	0.65	1.16	0.64
Mortality (total number)			
Tick-borne encephalitis	2	5	0
Lyme borreliosis	0	0	0
Rickettsiosis	0	2	1
Mortality [%]			
Tick-borne encephalitis (TBE)	3.86	8.06	0
Lyme borreliosis	0	0	0
Rickettsiosis	0	0.56	0.49
Estimated population of Mongolia (millions of inhabitants, according to UN)	3.027	3.076	3.122

2.4. Genus Hyalomma

Ticks from the genus *Hyalomma* occur in arid areas of southern Mongolia. This genus is represented by two species in Mongolia: *Hyalomma asiaticum* and *Hyalomma dromedarii.* Both species infest various domestic animals such as goats, donkeys, and camels (Dash, 1969). Recently, *Hy. asiaticum* ticks infected by Crimean-Congo haemorrhagic fever virus (CCHFV) were found in southern Mongolia (Voorhees et al., 2018).

2.5. Genus Rhipicephalus

Lastly, the genus *Rhipicephalus* is represented by the single species *Rhipicephalus pumilio* within Mongolia. These ticks were found in the deserts of southern Mongolia feeding on camels and pikas (Dash, 1969). Two Astrakhan fever *Rickettsia* strains (A-108 and A-167) were detected in *R. pumilio* in Russia (Eremeeva et al., 1994) and thus pose a possible threat to Mongolia.

3. Tick-borne pathogens in Mongolia

3.1. Tick-borne encephalitis virus

Tick-borne encephalitis virus has been repeatedly detected in Mongolia using either direct detection of TBEV on cell culture, or genomic RNA and anti-TBEV antibodies (Fig. 3). TBEV has been reported mostly from *I. persulcatus* (Boldbaatar et al., 2017). The highest prevalence of TBEV in questing *I. persulcatus* ticks was reported within the Selenge (3.2% on average, but locally over 6%) and Bulgan aimags (1.5% on average, but locally up to 7.5%) (Baasandavga et al., 2017; Frey et al., 2012; Muto et al., 2015). Unfortunately, the developmental stages of the infected ticks is not reported within the afore-mentioned references.

Walder et al. (2006) detected only 5% seropositive individuals among healthy volunteers within the Selenge aimag. Baasandavga at al. (2017) found more than 20% seropositive individual among healthy volunteers within Selenge and Darkhan aimags and more than 10% in 5 more aimags (Arkhangai, Bulgan, Dornod, Khuvsgul, Khentii) during a nationwide study. All these aimags with high TBEV human seroprevalence are located in the northern, taiga covered part of Mongolia with high activity of *I. persulcatus*.

On the other hand, sporadic TBE cases were reported also from other aimags, where *I. persulcatus* is not present. These could be either imported cases or autochthone cases caused by TBEV transmission by a different vector. The second possibility is very realistic as low TBEV prevalence has also been found in questing *D. silvarum* (2.9%) and *D. nuttalli* (nationwide only 0.61% but locally up to 8% in northern Selenge) (Baasandavga et al., 2017).

Genetic analyses showed that Mongolian TBEV isolates group within Siberian (Erdenechimeg et al., 2014; Frey et al., 2012) or Far-Eastern subtypes (Khasnatinov et al., 2010; Muto et al., 2015). Recently a new TBEV subtype was described in the Irkutsk Region of Russia (Demina et al., 2010; Kovalev and Mukhacheva, 2017; Zlobin et al., 2001; Zlobin and Malov, 2015), known as the Baikal subtype, which has been connected with one fatal case of meningoencephalitis in the Bulgan aimag (Khasnatinov et al., 2010; Kozlova et al., 2018). Despite the reported presence of TBEV in Mongolia, no information is readily available regarding potential animal reservoirs and thus further research into this is crucial. However, it would be expected that small mammals, such as rodents and hedgehogs, may serve as TBEV reservoirs as they are reported to be reservoirs within the Siberian part of Russia and in other east Asian countries (Bakhvalova et al., 2016; Yoshii et al., 2017). In previous studies, anti-TBEV antibodies have been found in important Mongolian livestock species including cattle (7%), horses (12%), sheep (9%), and goats (10%) indicating that these animals are exposed to TBEV and may also be possible TBEV reservoirs within Mongolia (Erdenechimeg et al., 2014). Apart from transmission via ticks, TBEV can be also transmitted by unpasteurized milk, and all the afore-mentioned livestock animals are currently used in Mongolia for milk production. Due to the nomadic lifestyle of many Mongolians, milk is often consumed unpasteurized and thus there is a risk of TBEV infection in humans. However, no studies have been conducted yet in Mongolia on the risk of human TBEV infection via consumption of unpasteurized milk.

No information is readily available on anti-TBEV vaccination statistics either. By analyzing available hospital data, Baasandavga et al. (2017) found notes about 225 confirmed TBEV cases in nine Mongolian aimags, which leads to an estimated infection rate of 0.75 per 10,000 inhabitants. These results are in concordance with data obtained from The Mongolian Ministry of Health, showing that about 50 people are hospitalized due to TBEV infection annually (Table 1), which is approximately 0.2 to 0.6 infected Mongolians per 10,000 inhabitants. It corresponds to the reported TBEV prevalence in Russia (Korenberg and Likhacheva, 2006). The TBEV fatality rate in Mongolia (about 10%) is also similar to that associated with the Siberian TBEV subtype (Gritsun et al., 2003).

3.2. Crimean-Congo hemorrhagic fever virus

CCHFV was recently detected within 1 of 1772 collected questing- and livestock-feeding adult *Hy. asiaticum* ticks collected from within the southern Mongolian aimag, Umnugobi (Voorhees et al., 2018). Despite such a low frequency of CCHFV occurrence in ticks, seroprevalence in tested human samples is quite high, reaching up to 2.63% in the southern Bayankhongor aimag. However, the seroprevalence is zero within the northern and central aimags of Khovd, Dundgovi, and Dornod, where *Hy. asiaticum* is not endemic (Voorhees et al., 2018). In Mongolia, anti-CCHFV antibodies have been found in various small mammals which may serve as virus reservoirs, such as the Tolai hare, pika, and long-tailed ground squirrel (Chumikhin et al., 1987), as well as small ruminants (Morikawa, 2013). Despite the relatively high seroprevalence, no human case of CCHFV infection requiring hospitalization is known from Mongolia, indicating that some cases may be misdiagnosed.

3.3. Borrelia burgdorferi sensu lato (s.l.)

The bacterial complex *Borrelia burgdorferi* sensu lato (s.l.) consists of several spirochete species, including *B. burgdorferi* sensu stricto (s.s.), *Borrelia garinii*, *Borrelia valaisiana*, *Borrelia afzelii*, *Borrelia spielmanii*, and *Borrelia lusitaniae*. Some of these species cause Lyme borreliosis and *B. burgdorferi* s.l. spirochetes have been repeatedly detected in high prevalence in questing adult *I. persulcatus* ticks within the northern aimags of Mongolia (Selenge, Bulgan, and Khuvsgul; Fig. 3) where they can reach an infection prevalence of up to 60% (Iwabu-Itoh et al., 2017; Masuzawa et al., 2014; Scholz et al., 2013). Anti-*Borrelia* antibodies were found in humans living in the northern aimags Bulgan, Dornogobi, Selenge, and Tov, in a prevalence of between 2–14%, depending on the geographical location (Walder et al., 2006). Anti-*Borrelia* antibodies were also found in numerous rodent species within Mongolia, including the Mongolian gerbil (prevalence ˜86%), ground squirrel (˜83%), striped dwarf hamster (almost 100%), and Siberian chipmunk (˜25%), which shows that these animals are frequently exposed to *Borrelia* spirochetes in Mongolia (Pulscher et al., 2018). The seroprevalence of anti-*Borrelia* antibodies in humans and in rodent species presumably serving as spirochete reservoirs in Siberia, parts of Russia and China, are similar to the values observed in Mongolia (Beklemishev et al., 2003; Margos et al., 2013; Rar et al., 2005; Takada et al., 1998).

Data from the Mongolian Ministry of Health shows that typically not more than 70 patients are treated for Lyme borreliosis annually (˜0.045-0.25 patients per 10,000 inhabitants; Table 1). This is lower than the reported incidences in Russia, where the prevalence of Lyme borreliosis reaches 0.4-0.6 patients per 10,000 inhabitants (Korenberg and Likhacheva, 2006). Considering the large difference in reported incidence of Lyme borreliosis between ecologically similar parts of Russia and Mongolia, it is likely that many Lyme borreliosis cases in Mongolia may be undiagnosed or misdiagnosed.

3.4. Borrelia miyamotoi

The bacterium *Borrelia miyamotoi* causes tick-borne relapsing fever (TBRF), and is a medically important pathogen in eastern Asia. Presence of *B. miyamotoi* spirochetes was confirmed in questing adult *I. persulcatus* ticks within the same northern aimags as *B. burgdorferi* s.l. (Fig. 3) but with a much lower infection prevalence (˜5%; Iwabu-Itoh et al., 2017). Despite this, there have been no reports of human infection caused by *B. miyamotoi* within Mongolia, which may again be due to misdiagnosis or lack of effective reporting system (Iwabu-Itoh et al., 2017; Taylor et al., 2013). In contrast to Mongolia, clinical cases of relapsing fever caused by *B. miyamotoi* infection have been reported from Japan and Russia (Platonov et al., 2011; Sato et al., 2014). Furthermore, *B. miyamotoi* has been found in China, South Korea, Japan, and Siberia, where it was identified in *I. persulcatus* as well as in other *Ixodes* species, at a prevalence of about 2–5% (Krause et al., 2015).

3.5. Anaplasma phagocytophilum and Anaplasma platys

Various *Anaplasma* spp. were detected in questing *D. nuttalli* and *I. persulcatus* ticks within the Selenge, Khentii, and Arkhangai aimags (von Fricken et al., 2018; Javkhlan et al., 2014; Karnath et al., 2016; Masuzawa et al., 2014). The prevalence of *A. phagocytophilum* in adult *I. persulcatus* varies, but averages 6% (Javkhlan et al., 2014; Karnath et al., 2016; Masuzawa et al., 2014), and is similar for male and female ticks (Karnath et al., 2016). Interestingly, no *A. phagocytophilum* was found in *I. persulcatus* nymphs, but only 13 individuals were tested (Karnath et al., 2016). Prevalence of *A. platys* is very low in adult *I. persulcatus,* reaching a maximum of 1% (Javkhlan et al., 2014). However, in adult *D. nuttalli* the prevalence of *A. platys* reaches up to 10%, while the prevalence of *A. phagocytophilum* is only 1% (Javkhlan et al., 2014)

Anti-*Anaplasma* antibodies have been found in humans living within Selenge, Tov, and Dornogobi aimags, varying between 2% to 75% (von Fricken et al., 2018; Walder et al., 2006; Fig. 3). Similarly, variable prevalence was also reported for livestock (sheep, goats, cattle, horses and camels), ranging from 10 to 75% within these same aimags (von Fricken et al., 2018). Anti-*Anaplasma* antibodies were detected in Mongolian gerbils (prevalence of up to 50%), ground squirrels (up to 75%), striped dwarf hamster (up to 100%), and Siberian chipmunk (up to 50%) showing that these animals are exposed to *Anaplasma*, and presumably also serve as reservoirs, despite the fact that no *Anaplasma* DNA was directly identified from these rodents (Pulscher et al., 2018).

Anaplasma phagocytophilum has been reported in *I. persulcatus* ticks within the countries surrounding Mongolia, but the prevalence is usually lower, reaching only approximately 3% (Jiang et al., 2011; Rar et al., 2005). No symptomatic human infection associated with *Anaplasma* has been reported in Mongolia, but infection was reported in the Chinese province of Inner Mongolia (Gaowa et al., 2018).

3.6. Anaplasma ovis

Anaplasma ovis, an important pathogen infecting small ruminants, was found in most Mongolian aimags (Enkhtaivan et al., 2019). Amongst sheep and goats in Mongolia, PCR-based detection revealed an infection prevalence of *A. ovis* of about 70% and seroprevalence ranging up to 100%. As *A. ovis* was found in questing adult *D. nuttalli* (but not *I. persulcatus*, *Ha. pospelovashtromae* or *Hy. asiaticum*), this tick species is considered to be its main vector in Mongolia (Enkhtaivan et al., 2019).

3.7. Candidatus Neoehrlichia mikurensis

Candidatus Neoehrlichia mikurensis was reported in questing nymphal and adult *I. persulacatus* ticks in Mongolia, with an infection prevalence of 1.5% (Karnath et al., 2016). In other parts of the world, *Candidatus* Neoehrlichia mikurensis has been identified in humans and animals, predominantly within individuals with immunodeficiency (Silaghi et al., 2016). However, *Candidatus* Neoehrlichia mikurensis has also been reported in otherwise healthy patients within the neighboring regions of China (Li et al., 2012) and thus increased attention should be paid to this pathogen within Mongolia as well.

3.8. Rickettsia spp

Three *Rickettsia* species were reported in Mongolia: *R. raoultii*, *R. sibirica*, and *Rickettsia tarasevichiae*, with the prevalence of *Rickettsia*-infected ticks in Mongolia being similar to that reported within Russia and China (Liu et al., 2015). *Rickettsia raoultii* and *R. sibirica* were detected in questing *D. nuttalli* ticks within the Khentii, Arkhangai, Dornod, Selenge, and Dornogobi aimags (Boldbaatar et al., 2017; Speck et al., 2012) (Fig. 3). The prevalence of *R. raoultii* was between 70–100%, as reported by Speck et al. (2012); however, Boldbaatar et al. (2017) reported an infection prevalence of only 10–17% in Mongolia. This large difference in reported infection prevalence between the two studies could be explained by the strong focality of *Rickettsia* spp., which can reach high prevalence in one area but be absent or present at low infection prevalence in another locality (Eremeeva, 2012). On the other hand, inter-annual variability of *Rickettsia* is low, and most probably would not have any effect on observed differences (Sprong et al., 2009). Compared to the prevalence of *R. raoultii*, the prevalence of *R. sibirica* appears to be much lower. *Rickettsia sibirica* was detected in questing adult *D. nuttalli* ticks in the Khentii, Dornod, Selenge and Arkhangai aimags, and overall it had an infection prevalence of only 8.5% (Speck et al., 2012). *Rickettsia tarasevichiae* was detected in questing *I. persulcatus* ticks within the Selenge aimag at an infection prevalence of approximately 20% (Boldbaatar et al., 2017).

Ecological studies on *Rickettsia* show that the major natural reservoirs for this species within Mongolia are Mongolian gerbils. Other susceptible small mammals include ground squirrels, striped dwarf hamsters, and Siberian chipmunks (Pulscher et al., 2018). Amongst Mongolian livestock, anti-*Rickettsia* antibodies were found in horses (up to 56%), cows (up to 38%), sheep (up to 31%), and goats (up to 20%), but only rarely in camels (up to 4%; von Fricken et al., 2018). *Rickettsia* seroprevalence amongst livestock in China and Russia reach similar levels to those reported in Mongolia (Igolkina et al., 2018a; Liu et al., 1995). However, there are no reports about *Rickettsia* (sero)prevalence in large wild animals, either for ungulates or carnivores.

Serological screens done on 397 healthy nomadic herders in the Selenge, Tov and Dornogobi aimags reported that anti-*Rickettsia* antibody seroprevalence varies between 4–30% and is highly dependent on the locality (von Fricken et al., 2018). Mongolian *Rickettsia* are known to be the etiologic agents causing spotted fever in travelers returning from Mongolia (Lankester and Davey, 1997; Lewin et al., 2003). Over 750 cases of tick-borne rickettsiosis (TBR) were reported by the Mongolian Ministry of Health from 2016 till October 2018, with only two of these cases being fatal. The annual TBR prevalence in Mongolians is therefore between 0.67 and 1.17 patients per 10,000 inhabitants, which is slightly higher than the average number of TBR cases in Russia (0.25-0.4 patients per 10,000 inhabitants), but still five to ten times lower than its prevalence in Altay and Krasnoyarsk regions, the two most affected regions in Russia (Parola et al., 2013; Shpynov et al., 2009; Tarasevich and Mediannikov, 2006)

3.9. Piroplasmorida parasites

Various *Theileria* and *Babesia* apicomplexans have been reported in Mongolia (Fig. 3). The species composition of Piroplasmorida parasites in Mongolia corresponds well to the situation within neighboring parts of Russia and China. In these countries, Piroplasmorida parasites can also be transmitted by other tick species which are not present in Mongolia (Rar et al., 2014; Yin et al., 1997). *Theileria equi* was reported in *D. nuttalli* ticks within the Tov aimag at an infection prevalence of ˜ 13% (Battsetseg et al., 2002, 2001). *Theileria orientalis* was reported in the Khentii aimag at an infection prevalence ranging from 3 to 73% (Altangerel et al., 2011) but the tick species in which it was found were not specified. These data indicate that *Theileria* parasites have focal distributions. Similarly, *Babesia caballi* has a variable infection prevalence of 15 to 52% in *D. nuttalli* ticks in Mongolia (Battsetseg et al., 2002, 2001). *Babesia microti* and *Babesia venatorum* were detected in 30% and 3% of *I. persulcatus* ticks, respectively, but they have not been found within *D. nuttalli* ticks (Karnath et al., 2016; Tuvshintulga et al., 2015a; 2015b).

DNA of *Ba. caballi* and *T. equi* have both been detected in horses, with a prevalence of 1 to 67% for *Ba. caballi* and 13 to 93% for *T. equi*, depending on the locality studied within Mongolia (Battsetseg et al., 2002; Munkhjargal et al., 2013; Rüegg et al., 2007; Sloboda et al., 2011; Tarav et al., 2017). Similar to the prevalence of the Piroplasmorida parasites, the seroprevalence against these two equine pathogens were high, ranging from 18 to 79% for *Ba. caballi* and 17 to 96% for *T. equi* (Boldbaatar et al., 2005; Munkhjargal et al., 2013; Rüegg et al., 2007). *Theileria equi* DNA was detected in 84% of tested Przewalski horse samples (16 positive horses of 19 tested) from Hustain National Park (Tov aimag; Rüegg et al., 2007, 2006) and this pathogen was responsible for 19% of Przewalski horse mortalities in the Hustain National Park from 2012 to 2015. Thus, this Piroplasmorida parasite is one of the major threats to Przewalski horses within this area (Rüegg et al., 2006). A much lower Piroplasmorida parasite prevalence was detected in Przewalski horse samples collected from within the Gobi B area (14%, Robert et al., 2005).

Babesia bigemina, *Babesia bovis*, *Babesia ovata* and *T. orientalis* DNA were detected within Mongolian bovine hosts in the localities indicated in Fig. 3. The prevalence of *Ba. bigemina* ranged from 2 to 20% in the Hentii, Uvs, and Uvurkhangai aimags (Sivakumar et al., 2012), while the prevalence of *Ba. bovis* ranged from to 3 to 26% in the same aimags (Altangerel et al., 2012). The prevalence of *Ba. ovata* is much lower, ranging from 0 to 9%, and was detected only in the Khentii aimag (Yoshinari et al., 2013). The prevalence of *T. orientalis* was the highest of these four Piroplasmorida parasites, ranging from 9 to 66% in Khentii, Uvs, and Uvurkhangai (Altangerel et al., 2011). However, no Piroplasmorida DNA has been detected in samples from camels and dogs (Sloboda et al., 2011) and no information is available on the presence of Piroplasmorida parasites in other domestic or wild living animals in Mongolia.

Regarding its presence in humans, *Ba. microti* DNA was found in 3% of healthy farmers in Khutul city (Selenge aimag) with the seroprevalence reported to be 7%, without any reported fatalities (Tuvshintulga et al., 2015a; Hong et al., 2014). *Babesia venatorum* was found in about 3% of adult questing *I. persulcatus* ticks from Selenge, but not in nymphs collected in the same locality (Tuvshintulga et al., 2015b; Karnath et al., 2016). Despite the presence of several species of Piroplasmorida, which are potentially pathogenic for humans in Mongolia, no literature is currently available describing human infection by Piroplasmorida apicomplexans. This is unexpected as human babesiosis, caused by *Ba. microti,* has been reported within the neighboring provinces of China (Zhou et al., 2014). This leads to assumption that such cases of this TBP could again be either misdiagnosed or unreported in Mongolia.

4. Conclusion

Several tick species and TBPs have been described within Mongolia. The prevalence of TBPs differs depending on the locality, season and year of study. However, it is unclear whether differences in TBPs prevalence described between Mongolia and its neighboring countries are due to the harsher climate in Mongolia, leading to lower overall abundance of vector ticks, and more variable infection prevalence in the ticks, or the general low intensity of research into ticks and TBPs in Mongolia. Thus, it is necessary to perform studies of longer duration and covering several localities during several seasons within Mongolia to better characterize the spatial and temporal distribution of ticks and TBPs in Mongolia, as well as describe their dependence on different biotopes and microclimate conditions.

Numerous wild and livestock species have been reported to contain antibodies against TBPs and can potentially serve as TBPs reservoirs in Mongolia, and many of these animals are commercially important (sheep, goats, cattle, and horses). Typically, small rodents, such as Mongolian gerbils, Siberian chipmunks, and striped dwarf hamsters, serve as reservoirs for many TBPs in Mongolia. Additionally, equine Piroplasmorida are circulating in Mongolian horse populations and is responsible for a high number of mortalities in endangered, newly reintroduced Przewalski horses. However, the effect of ticks and TBPs on animal production and the subsequent economic losses caused to Mongolian agriculture have not been established. Furthermore, no investigation has been performed into the massive threat that consumption of unpasteurized milk or other animal products poses to Mongolians regarding TBP transfer.

From the information published on the seroprevalence of TBPs in the heathy Mongolian population, antibodies against TBEV, CCHFV, *Anaplasma*, *Borrelia*, and *Rickettsia* bacteria as well as against *Ba. microti* are present in the population. However, reports regarding cases of TBP infection seem low, especially in comparison to neighboring countries. Therefore, thorough independent investigation into the incidences and sources of TBP infections in Mongolians needs to be performed. Such information is imperative when considering potential tick-control in livestock production and zoonosis disease control strategies.

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