One Health 19 (2024) 100897

Contents lists available at ScienceDirect

One Health

journal homepage: www.elsevier.com/locate/onehlt

Distribution and diversity of ticks determined by environmental factors in Ningxia, China

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ARTICLE INFO

Keywords:
Field survey
Ecological niche modelling
Environmental factors
Greening program

ABSTRACT

Ticks are important vectors of zoonotic pathogens, and represent an increasing threat for human and animal health. Considering the complex natural environments of Ningxia Hui Autonomous Region, China, we expect the diverse tick species in this region. Here, we conduct a field survey on parasitic and host-seeking ticks. A total of 10,419 ticks were collected, which belonged to nine species of four genera. There were significant differences in terms of vegetation index, altitude, and seven climatic factors among the four tick genera —*Hyalomma, Dermacentor*, *Haemaphysalis,* and *Ixodes*, except between *Haemaphysalis* and *Ixodes*, where no significant differences were observed in these factors. The ecological niche modelling revealed that the suitable habitats for *Hyalomma asiaticum* was in the northwest Ningxia, with annual ground surface temperature as the most important factor. The suitable area for *Dermacentor nuttalli* was in the southwest and eastern regions of Ningxia with elevation as the highest contribution. *D. silvarum* was best suited to the southern Ningxia also with elevation as the most important factor. The four tick species including *Haemaphysalis longicornis*, *Hae. qinghaiensis*, *Hae. japonica*, and *Ixodes persulcatus* were best suited to the southernmost Ningxia with annual precipitation as the main factors for *Hae. longicornis* and elevation for the other three ticks. The results of predicted potential distribution of different tick species provide a scientific basis for the prevention and control of ticks and tick-borne diseases in the region. Furthermore, the subsequent impacts of the Greening Program to regain forests and grasslands from former agricultural lands in Ningxia on tick population dynamics deserve further investigation.

1. Introduction

Ticks are obligate blood-feeding arthropod vectors distributed around the world, and capable to transmit the most diverse pathogens, including bacteria, protozoa, fungi, nematodes, and viruses, to humans and animals [1] Ticks are seen year-round in tropical regions, while their distribution in temperate regions is seasonally dependent. As with other arthropods, the abundance and distribution of ticks and their hosts primarily rely on habitat suitability, which is largely determined by climatic and environmental conditions. The distribution of ticks is closely related to the natural environment, with obvious regional and seasonal characteristics [2,3]. Moreover, climate factors such as temperature, humidity and precipitation affect the growth, development and survival of ticks [4]. The expansion of suitable habitats has led to the increases in tick populations, which may subsequently promote the spread of tick-borne diseases [5]. The continuous emergence and increasing number of tick-born of tick-borne diseases have caused a global concern [6,7].

In China, the emerging tick-borne infections have become an increasing public health threat [8]. The recent high throughput next

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https://doi.org/10.1016/j.onehlt.2024.100897
Received 23 January 2024; Received in revised form 22 August 2024; Accepted 16 September 2024
Available online 17 September 2024
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generation sequencing technique has identified hundreds of RNA viruses from 31 tick species collected in mainland China [9], showing great potential risks for humans and animals. Although the advances in and application of molecular technologies have resulted in the efficient discovery of novel tick-associated agents [10], the increase in tick vectors and their animal hosts should be the important reason for effective transmission of the zoonotic diseases [11]. Considering the China's policies for ecosystem services have generated good ecological effects

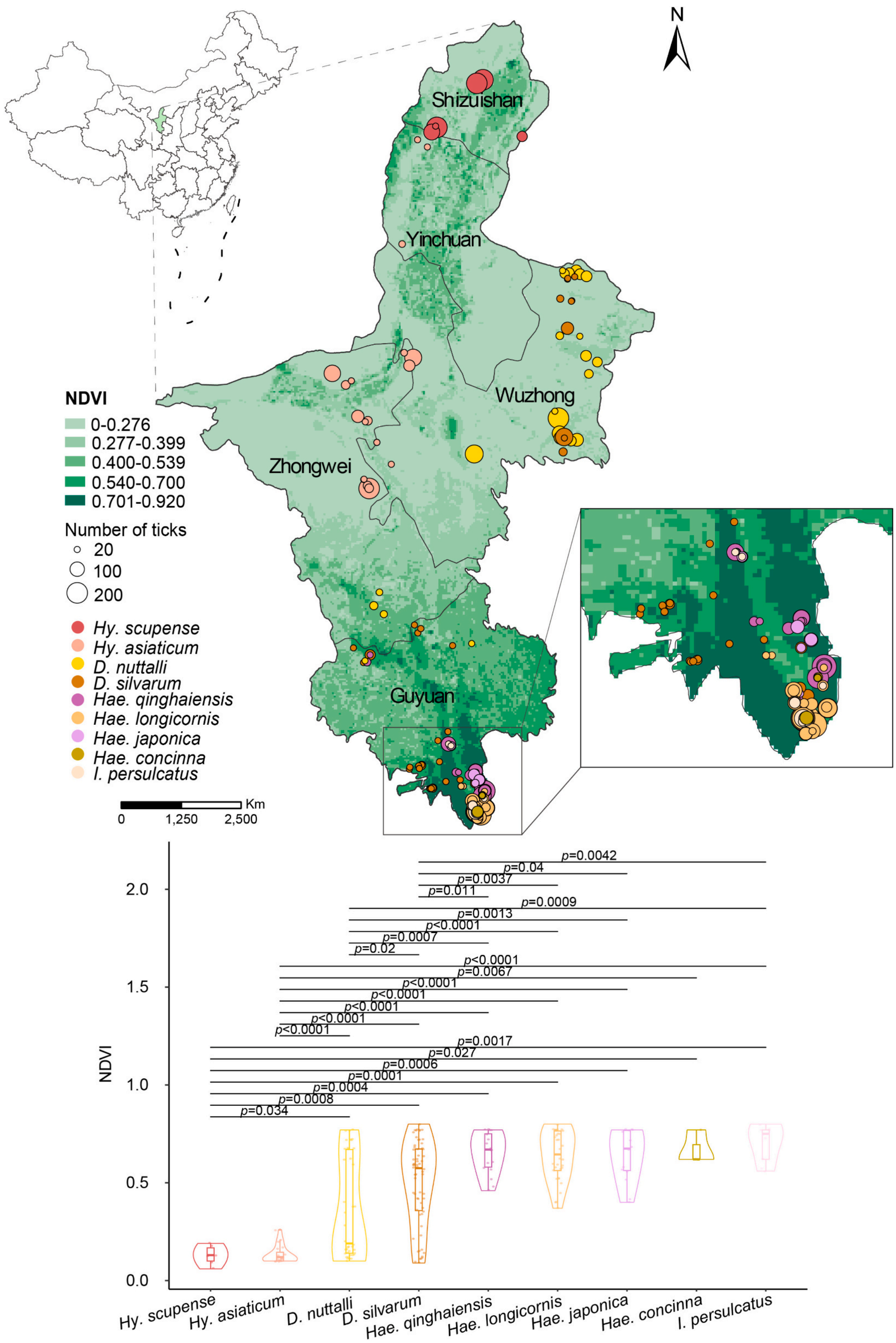

Fig. 1. Geographical distribution of tick samples in relation to normalized difference vegetation index.
(A) Collection location of different tick species in Ningxia. The base map is normalized difference vegetation index (NDVI). The colors of solid circles represent different tick species. The circle size represents the number of ticks collected in the location. (B) The pairwise comparisons of NDVI between tick species. Their significant differences were examined by Wilcoxon rank sum test.

since the mid-1990s [12], we assume that grass replanting and reforestation might have increased the abundance of ticks, and subsequently might facilitate the transmission of tick-borne pathogens. However, there has been no study to investigate the environmental and ecological impacts on distribution and diversity of ticks in China.

Here we conducted a field survey on parasitic and host-seeking ticks in Ningxia Hui Autonomous Region of northern China with an area of 66,400 km^2, where the green coverage and animal husbandry have significantly increased after grass replanting and reforestation [13]. The objectives of this study were to investigate the presence of tick species, to map the distribution of each tick species in relation to environmental factors, to quantify effects of major environmental factors, to predict the suitable habitats of different tick species, and ultimately to clarify the impacts of green development on tick population dynamics for better understanding public and veterinary health influence.

2. Materials and methods

2.1. Study area

Ningxia Hui Autonomous Region (abbreviated as Ningxia) is located in the northern inland of China between $104^\circ 17' \sim 107^\circ 39'$ E longitude and $35^\circ 14' \sim 39^\circ 23'$ N latitude, with a total area of 66,400 km^2 and a population about 7.2 million people. The average elevation of Ningxia is over 1000 m above sea level. The agricultural activities and overgrazing had resulted in severe ecosystem degradation of Ningxia in last century. The Greening Program to regain forests and grasslands from former agricultural lands was initiated in this region in 2000 [12,13]. The ecosystem conversion policies have led to an increase of grassland and forest areas from 7.74 % to 33.2 %.

2.2. Field survey of ticks

From April–May 2022 to March–May 2023, field surveys of ticks were conducted in all five cities (Shizuishan, Yinchuan, Wuzhong, Zhongwei, and Guyuan) across Ningxia region (Fig. 1). The ticks were collected by dragging a 1-m^2 standard flannel flag over vegetation, or from domestic animals such as cattle, sheep, and goats. The number of sampling sites in each region was determined by livestock density and farmers' willingness to participate in the survey. The latitude and longitude of each collection site were recorded. Morphological identification was done by an entomologist (YS) using a stereoscopic microscope to identify the species, sex, and developmental stage of each tick [14].

2.3. Data collection of environmental factors

Data concerning ecological and climatic factors were collected to study potential determinants for the spatial distribution of different tick species in Ningxia. The ecological and climatic data including normalized difference vegetation index (NDVI), elevation data (DEM, Digital Elevation Model), annual precipitation (mm), annual evaporation (mm), annual average relative humidity (%), annual average temperature (°C), annual average ground surface temperature (°C), annual average pressure (hPa), and annual sunshine duration (h) were obtained from the Resource and Environment Science and Data Center (http://www.resdc.cn). All the data regarding environmental factors were from 2020, because the field survey on ticks were conducted in 2022 and the data from 2020 were the available data from the closest time period.

2.4. Data management and statistical analysis

Each collection site of ticks was geo-referenced to a digital map of Ningxia according to the latitude and longitude. Thematic maps showing the geographical distribution of each tick species were produced with ArcGIS (version 10.6; ESRI, Redlands, CA, USA) by using each of the above ecological and climatic elements as the background. Two-tailed Wilcoxon's rank-sum test was used to determine statistically significant differences in environmental factors between tick species. R v.4.3.1 was used for the above analysis. A p-value <0.05 was considered statistically significant.

2.5. Predicting potential distribution of each tick species by modelling

Ecological niche modelling was used to predict the suitable habitat of each tick species [15]. Different combinations of variables and parameters were evaluated to avoid possible collinearity and overfitting [16,17]. ENMTools (version 1.4.4) with Akaike information criterion was used to select models [18–20] (Supplemental Data 1 for a detailed description of model building). Finally, the habitat of each tick species was overlapped on a map to show the potential distribution of different tick species in Ningxia.

3. Results

3.1. Tick survey

A total of 10,419 ticks were collected from 149 sampling sites in Ningxia, and nine tick species belonging to four genera were dentified, including *Hyalomma scupense*, *Hy. asiaticum*, *Dermacentor nuttalli*, *D. silvarum*, *Haemaphysalis longicornis*, *Hae. qinghaiensis*, *Hae. japonica*, *Hae. concinna*, and *Ixodes persulcatus*. The species and numbers of ticks collected at each survey site varied from area to area, showing obviously geographical differences in the distribution of tick species (Fig. 1). A total of 968 *Hy. scupense* were collected from Shizuishan City of the northernmost part of Ningxia, including 418 males and 550 females. *Hy. asiaticum* was mainly distributed in Zhongwei City in the west of Ningxia, with a total of 883 individuals (91.9 %). More than two thirds of *D. nuttalli*, (69.7 %) were distributed in the eastern part of Wuzhong City. *D. silvarum* mainly distributed in Guyuan City (76.3 %) in the south of Ningxia, and the rest were cross-distributed with *D. nuttalli* in the east of Wuzhong City. The remaining samples of four *Haemaphysalis* species and *I. persulcatus* were collected from Liupan Mountain of Guyuan City, south of 36.14°N latitude (Fig. 1). The sex, development stages, and blood-sucking status of each tick species are summarized in Table 1. Given ticks were captured on animals and by dragging over vegetation, we compare the differences in tick species distribution between the two approaches. Both tick species in the genus *Hyalomma* were collected from animals, with more than 80 % being unfed, and only one free-living tick was collected on vegetation. The two tick species in the genus *Dermacentor* were mostly collected from animals, with more unfed ticks than fed ones, and a small portion was collected from vegetation. The number of *Hae. longicornis* collected from vegetation accounted for approximate half of the total, and a little more unfed ticks were collected from animals than fed ones. For *Hae. qinghaiensis*, *Hae. japonica*, and *I. persulcatus*, majority were from vegetation. Whereas most *Hae. concinna* were fed from animals (Table 1). As to the animal hosts of ticks, 5.9 % *Hy. scupense* and 75.1 % *Hy. asiaticum* were collected from sheep, and and the remaining from goats. *D. nuttalli* (82.0 %), *D. silvarum* (86.2 %), *Hae. longicornis* (96.4 %), *Hae. qinghaiensis* (84.2 %) and *Hae. japonica* (60.1 %) were frequently collected from sheep. A small portion of *D. silvarum*, *Hae. longicornis*, and *Hae. qinghaiensis* were collected from cattle. In contrast, about two third *Hae. concinna* were collected from cattle, the remaining from sheep. Only four *I. persulcatus* were collected from sheep, the remaining 306 were free-living from vegetation (Table S1).

3.2. Effect of environmental factors on distribution of tick species

Given the obvious aggregation of different tick species, we mapped the distribution of each tick species in relation to environmental factors, and quantified effects of major environmental factors. We first analyzed

Table 1
The summary of ticks collected in Ningxia Hui Autonomous Region.

Tick species	Developmental stage			From animals		From vegetation	Total
	Male	Female	Nymph	Fed	Unfed		
Hyalomma scupense	418	550	0	168	799	1	968
Hyalomma asiaticum	415	546	0	153	808	0	961
Dermacentor nuttalli	733	983	0	641	959	116	1716
Dermacentor silvarum	607	803	1	299	966	146	1411
Haemaphysalis longicornis	532	968	566	417	593	1056	2066
Haemaphysalis qinghaiensis	593	991	538	374	438	1310	2122
Haemaphysalis japonica	188	274	288	56	102	592	750
Haemaphysalis concinna	17	76	22	68	23	24	115
Ixodes persulcatus	106	204	0	4	0	306	310
Total	3609	5395	1415	2180	4688	3551	10,419

the effects of vegetation factors on the distribution of tick species (Fig. 1), and found that the NDVI of the two *Hyalomma* species was significantly lower than that of other tick species (all $p < 0.05$). The NDVI of the four *Haemaphysalis* species and *I. persulcatus* was significantly higher than that of other tick species (all $p < 0.05$). Different from the above genera, there was a significant difference between the two species of *Dermacentor* ($p = 0.0017$), and the NDVI of *D. silvarum* was higher than that of *D. nuttalli*.

Since the distribution range of the four *Haemaphysalis* species was almost identical, we combined the four tick species of the genus *Haemaphysalis* in the subsequent analysis. We analyzed the effect of DEM on the distribution of tick species (Fig. 2a). The DEM of areas with two tick species in the genus of *Hyalomma* was significantly lower than that of other ticks (all $p < 0.002$). The DEM of the distribution area of *Hy. scupense* was also significantly lower than that of *Hy. asiaticum* ($p = 0.0004$). For the two species of *Dermacentor* ticks, the DEM of the area where the *D. nuttalli* was located was significantly lower than that of the *D. silvarum* ($p = 0.0013$). The DEM of *Haemaphysalis* and *I. persulcatus* were significantly higher than those of other tick species (all $p < 0.005$).

We compared tick distribution with the association of climatic factors. The area where the *Hy. scupense* was located had the longest annual sunshine duration, ranging from 2974 to 3027 h with a median of 2978.5 h, followed by *Hy. asiaticum* (2571–3008 h, median: 2676 h) (Fig. 2b). The annual sunshine duration in the distribution areas of the two *Dermacentor* species was significantly lower than that of *Hyalomma* ($p < 0.01$).

We analyzed the effect of precipitation on the association with the distribution of different tick species (Fig. 3a), and found that the annual precipitation in the distribution areas of *Hy. scupense*, *Hy. asiaticum*, *D. nuttalli*, *D. silvarum*, *Haemaphysalis* and *I. persulcatus* gradually increased. There were significant differences in annual precipitation between two species in the genus *Hyalomma* and two species in the genus *Dermacentor*. On the contrary, the annual average ground surface temperature in the areas of above tick species showed a gradual decreasing trend (Fig. 3b). There was significant difference between the two species in the genus *Dermacentor* ($p = 0.0021$).

Additionally, considering that annual average pressure is closely related to DEM, average temperature is closely related to DEM, annual sunshine duration and annual evaporation, and annual average relative humidity is closely related to annual precipitation, the association between the four factors and the distribution of each tick species is not described in detail, as shown in Supplementary Materials (Fig. S1-S2).

3.3. Prediction of potential habitats for seven tick species

We used niche models to predict the suitable habitat of each tick species. As fewer than five sites were investigated for *Hy. scupense* and *Hae. concinna*, model predictions could not be made. Therefore, the potential distribution was predicted only for seven tick species. After using Pearson correlation analysis, it was found that different environmental factors were highly correlated ($r \geq 0.9$), so these factors were automatically excluded from the prediction model. Different tick species had different environmental factors included in the final prediction model, with area under curve (AUC) values ranging from 0.807 to 0.997 (Table 2; Fig. S3), indicating that all models had good goodness of fit.

The model prediction results of *Hy. asiaticum* were excellent (AUC = 0.944), and its suitable habitats were mainly distributed in the northwestern region of Ningxia (Fig. 4a). Annual ground surface temperature (%Cont = 57.2) was the most important factor. The highest permutation importance (PI) among the variables in the model was the annual ground surface temperature (PI = 52.9). The most suitable habitat for *Hy. asiaticum* was the area with an annual ground surface temperature of 13 °C, NDVI of 0.1, DEM of 2400 m, average temperature of 10 °C, and relative humidity of 48 % (Fig. S4).

The model prediction result of *D. nuttalli* was good (AUC = 0.865), and its suitable area was the widest, mainly distributed in the southwest and eastern regions of Ningxia (Fig. 4b). According to the results of niche prediction model, elevation, temperature and NDVI were the main factors affecting the suitable habitat of *D. nuttalli*. Among them, DEM (% Cont = 45.1) had the highest contribution, while temperature had the highest PI of 52.9. The most suitable living environment for *D. nuttalli* was 600 m above sea level, annual average temperature of 7 °C, and NDVI of 0.9 (Fig. S5).

The model predicted good result of *D. silvarum* (AUC = 0.807), and its suitable habitat was mainly distributed in Guyuan City, southern Ningxia (Fig. 4c). DEM was the most important factor affecting the suitable habitat of *D. silvarum* (%Cont = 44.6, PI = 78.3). The response curve showed that the optimal DEM for survival of *D. silvarum* was 500 m, and its adaptability gradually decreases with the increase of DEM. (Fig. S6).

Although the environmental factors included in the model were slightly different among the three tick species of the genus *Haemaphysalis*, the predicted habitat areas of them and *I. persulcatus* were all concentrated in Liupanshan mountain, the southernmost part of Ningxia (Fig. 4d-g). The most factors affected the potential distribution of *Hae. longicornis*, of which annual precipitation had highest %Cont (50.8) with a PI of 86.9. DEM was the main factor influencing the potential distribution of *Hae. qinghaiensis* (%Cont = 41.9) and *Hae. japonica* (%Cont = 41.9). The annual precipitation was positively correlated to the habitat suitability of *Hae. longicornis*. DEM (%Cont = 50.8, PI = 86.9), followed by NDVI (%Cont = 30.3) were the main influencing factors of *I. persulcatus* (Table 2). The response curves of the above four tick species are shown in Fig. S7–10.

Finally, we overlaid the suitable habitat of each tick species to make a prediction map of the above seven tick species in Ningxia (Fig. 4h). It was found that their distribution ranges were overlapped in Ningxia, and more than two tick species might exist simultaneously in same areas. The suitable habitats of *Hy. asiaticum* and *D. nuttalli* overlapped in the northern and western regions. The tick species with overlapping suitable habitats in the southern region were *D. nuttalli* and *D. silvarum*. The most overlapping tick suitable habitats were in the southernmost Ningxia, where there were *D. nuttalli*, *D. silvarum*, *Hae. longicornis*, *Hae.*

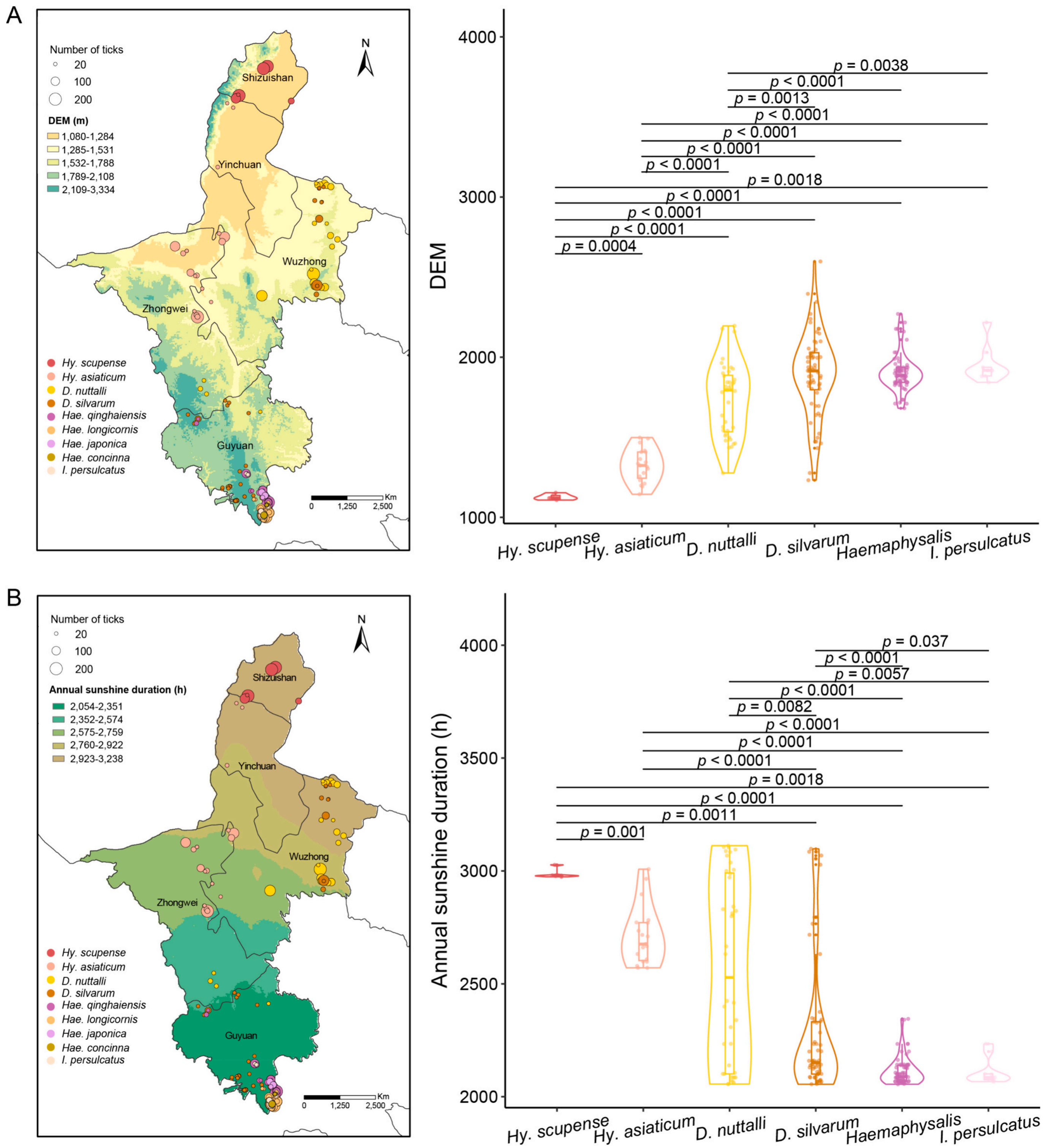

Fig. 2. Geographical distribution of tick samples in relation to elevation and annual sunshine duration.
(A) Geographical distribution of tick samples with elevation as the base map (left), and differences in elevation between each tick species measured by Wilcoxon rank sum test (right). (B) Geographical distribution of tick samples with annual sunshine duration as base map (left), and differences in annual sunshine duration between each tick species measured by Wilcoxon rank sum test (right).

qinghaiensis, *Hae. japonica*, and *I. persulcatus*. Notably, there were seven tick species in Guyuan City, which was a suitable habitat for ticks.

4. Discussion

Ningxia is one of the priority regions for western development in China. The Greening Program to regain forests and grasslands from former agricultural lands initialized by the Chinese central government in the mid-1990shas significantly increased the green coverage and animal husbandry in Ningxia region [12,13,21], which might have subsequently increased the abundance and diversity of ticks and animal hosts. This prompts us to conduct a field survey on tick in this region,

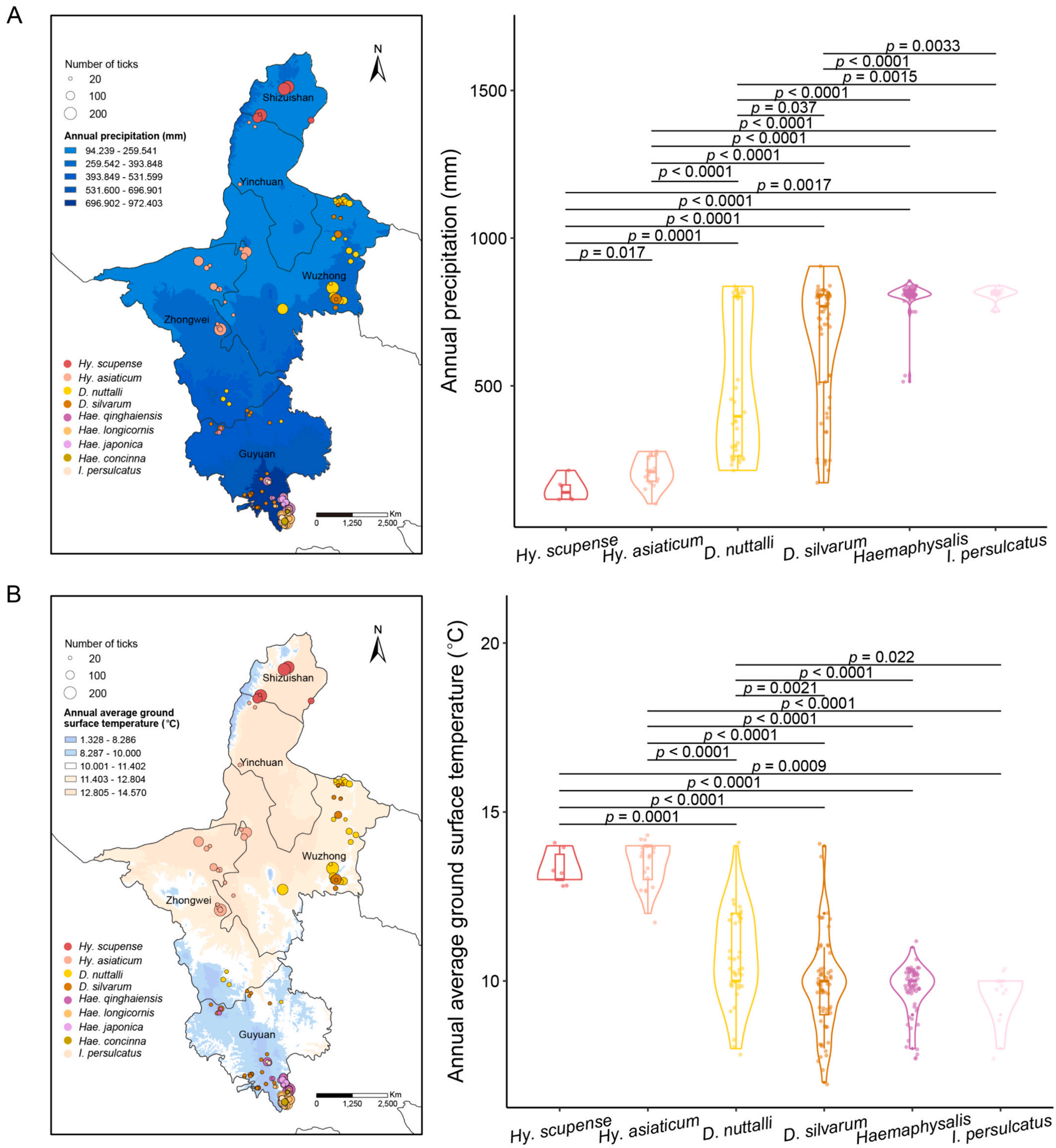

Fig. 3. Geographical distribution of tick samples in relation to annual precipitation and annual average ground surface temperature.
(A) Geographical distribution of tick samples with annual precipitation as the base map (left), and differences in annual precipitation between each tick species measured by Wilcoxon rank sum test (right). (B) Geographical distribution of tick species survey based on annual average ground surface temperature (left), and differences in annual average ground surface temperature between each tick species measured by Wilcoxon rank sum test (right).

and further investigate the environmental factors determining their presence. Two previous tick surveys conducted in specific regions of Ningxia were published in Chinese journals. One study collected 141 ticks from the Liupan Mountain area [22], which included *I. persulcatus*, *Ixodes ovatus*, *Hae. concinna*, *Rhipicephalus sanguineus*. Among them, only five *I. ovatus* and two *R. sanguineus* were collected, and these two species were not found in the current study. Another study collected 23 *Argas reflexus* ticks from a bird cave of *Pyrrhocorax pyrrhocorax* [23]. While, the current study collected 10,419 ticks from 149 survey sites across the entire Ningxia region, identifying nine tick species of four genera, which has largely clarified the distribution of major tick species in Ningxia. The geographical distributions of different tick species are clustered in the areas with distinctive environmental factors and ecological landscapes. We then use modelling approach by including these environmental

Table 2
The area under curve (AUC), percentage contributions (%Cont) and permutation importance (PI) of variables included in the Maxent models for seven tick species.

	Hy. asiaticum		*D. nuttalli*		*D. silvarum*		*Hae. longicornis*		*Hae. qinghaiensis*		*Hae. japonica*		*I. persulcatus*	
	AUC = 0.944		AUC = 0.865		AUC = 0.807		AUC = 0.997		AUC = 0.996		AUC = 0.992		AUC = 0.992	
Variable	%Cont	PI	%Cont	PI	%Cont	PI	%Cont	PI	%Cont	PI	%Cont	PI	%Cont	PI
Normalized difference vegetation index	17.2	24.8	17.8	9.3	22.5	18.3	3.8	0.8	18.4	2.2	1.7	1.1	30.3	0.3
Annual precipitation	×	×	×	×	×	×	50.8	86.9	×	×	31.8	52.2	21.4	0.3
Annual average relative humidity	4.9	8.8	×	×			5.5	0.9	×	×	×	×	×	×
Annual sunshine duration	×	×	×	×	32.9	3.4	2.7	2.3	10.2	8.6	6	0.6	0.4	7.7
Annual evaporation	×	×	×	×	×	×	15.6	5.5	29.5	56.2	17.3	0.2	0.5	2
Annual average ground surface temperature	57.2	38.2	×	×	×	×	×	×	×	×	×	×	×	×
Annual average temperature	9.6	8.4	37.1	52.9	×	×	×	×	×	×	7.1	3.6	9.7	4.2
Annual average pressure	×	×	×	×	×	×	7.9	1.7	×	×	×	×	×	×
Elevation	11.1	19.8	45.1	37.8	44.6	78.3	13.7	1.9	41.9	32.9	36	42.3	37.7	85.5

Note: Variables without any values (indicated by ×) were removed because of high cross-correlations.

factors to predict their suitable habitats and potential distribution areas. Our findings provide the essential information for evaluating the effects of the Greening Program on tick vectors. More importantly, this also remind us the potential public health consequences, because the change in the abundance and diversity of ticks and animal hosts may favor the re-construction of tick vector enzootic cycles, and consequently lead to the risk for emerging tick-borne diseases. An example is that the reforestation in northeastern USA during the 20th century has increased the population of white-tailed deer, which greatly amplified the abundance of *Ixodes scapularis* ticks, leading to emergence of Lyme disease [24]. A previous study in China indicates that the reduction in forest areas might lead to decrease in tick distributions and populations in central and southern China [25]. Another study reveals that 10 % increase in shrub, forest, and rain-fed cropland areas result in 51 %, 51 %, and 90 % increase, respectively in human severe fever with thrombocytopenia syndrome (SFTS) [25], which is an emerging tick-borne disease primarily transmitted by *Hae. longicornis* ticks in China [26]. Further surveillance and investigations should be enhanced for better understanding the impacts on public health.

In addition to vegetation and climate factors, agricultural activities can also influence the geographical distribution and population dynamics of each tick species. Unfortunately, we did not assess the impact of agricultural activities because they are difficult to be quantified. NDVI is considered as one of the most important effects of the Greening Program, and has been investigated for its association with the distribution of each tick species in this study. We found that NDVI differed significantly in the distribution areas of different tick species (Fig. 1), and it was an influential factor in the prediction model of suitable habitat for every tick species (Table 2), indicating that NDVI was an important determinant of the distribution of different tick species. As mentioned above, grass replanting and reforestation in Ningxia region since the mid-1990s have increased vegetation coverage [12], and consequentially expanded suitable habitats, which can substantially lead to the increases in tick populations and tick-borne diseases [5]. The climatic conditions, vegetation types and animal distribution are diverse in relation to altitude, and different tick species have corresponding altitude areas suitable for survival [27]. Our study found that elevations determine the distribution of tick species and contribute significantly to the prediction of suitable habitat for most tick species.

Both association analysis and modelling prediction revealed that the specific climate factors play a role in determining the distribution and range of different tick species, supporting the possible impacts of climate factors on tick activity and survival as proposed by the habitat suitability studies [28,29]. The climate factors may further influence disease transmission patterns by altering tick phenology [30].

Both *Hy. asiaticum* and *Hy. scupense* are mainly distributed in desert and arid desert environments in the northwestern region of Ningxia, where there is a relatively low altitude, low rainfall, and long sunshine hours, resulting in drought and low NDVI that facilitate the growth of *Hyalomma* ticks [31,32]. In contrast to the results of previous study in Xinjiang that *Hy. asiaticum* was mainly affected by precipitation-related climatic factors, we found that potential distribution of this tick species is primarily influenced by temperature-related climatic factors [33]. At the same time, our predicted suitable habitat for *Hy. asiaticum* in Ningxia spans the Yellow River basin, with a rich diversity of wildlife and birds, which serve as a natural host for the tick and enable it to thrive. In addition, migration of birds leads to passive movement of ticks, thus expanding the potential distribution of ticks. Hundreds of cases of infection with Crimean-Congo hemorrhagic fever virus (CCHFV) have been reported in Xinjiang, mainly due to bites from the *Hy. asiaticum* [34]. Therefore, surveillance and prevention of tick-borne pathogens in the distribution areas of *Hyalomma* should be enhanced.

The ecological niche of tick species is complex, and key environmental predictors differ even within the same genus. For example, *Hae. longicornis* is mainly associated with annual precipitation, while *Hae. japonica* and *Hae. qinghaiensis* are mainly affected by DEM. *Hae. qinghaiensis* is a typical three-host tick, which has been reported only in China [35,36]. It is especially prevalent in the high altitude western plateau area. *Hae. longicornis* has been reported to carry severe fever with thrombocytopenia syndrome virus (SFTSV) in Xinjiang of northwest China [37], suggesting that *Hae. longicornis* in Ningxia may carry SFTSV. There is a risk of transmission of SFTSV to humans.

5. Conclusion

In summary, the Ningxia Hui Autonomous Region, China has a diversity of tick species, and the distributions of each tick species is related to specific environmental and ecological factors. By using niche models combined with relevant environmental data, The suitable habitats and potential distribution of seven tick species were predicted by ecological niche modelling. NDVI, annual precipitation, and elevation are the main factors influencing tick distribution. These findings have provided the essential information for evaluating the effects of the Greening Program on tick vectors, and highlight importance for enhanced surveillance of ticks and tick-borne pathogens in the region.

CRediT authorship contribution statement

Di Tian: Writing – original draft, Data curation. **Xiao-Ming Cui:** Investigation. **Run-Ze Ye:** Formal analysis. **Yu-Yu Li:** Formal analysis. **Ning Wang:** Investigation. **Wan-Ying Gao:** Investigation. **Bai-Hui Wang:** Investigation. **Zhe-Tao Lin:** Investigation. **Wen-Jie Zhu:** Investigation. **Qiu-Shi Wang:** Investigation. **Ya-Ting Liu:** Data curation. **Hua Wei:** Investigation. **Yi-Fei Wang:** Investigation. **Yi Sun:** Data curation. **Xiao-Yu Shi:** Data curation. **Na Jia:** Data curation. **Jia-Fu Jiang:** Data curation. **Wu-Chun Cao:** Writing – review & editing, Conceptualization. **Zhi-Hong Liu:** Writing – review & editing, Conceptualization.

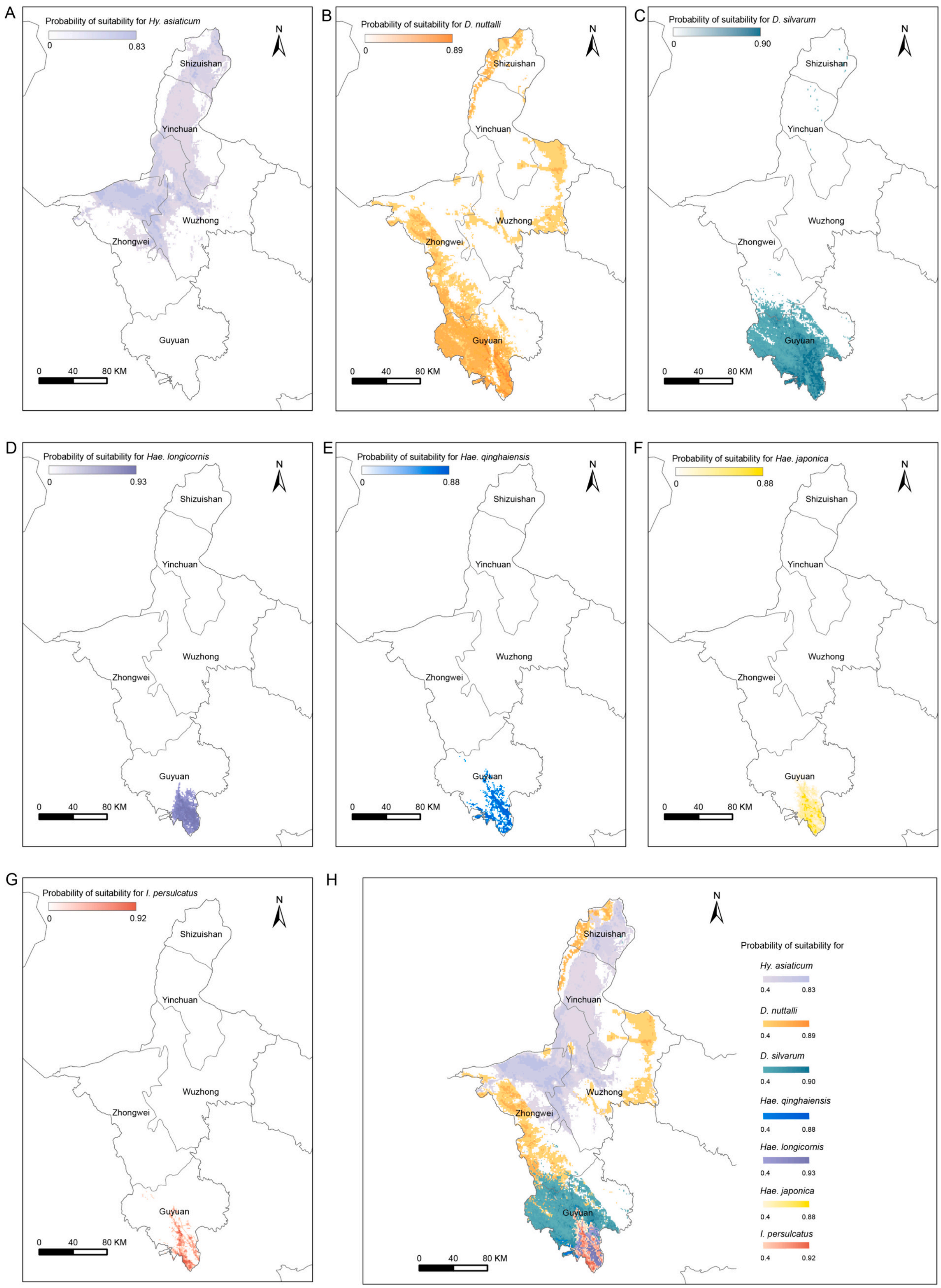

Fig. 4. Potential distribution map of seven tick species predicted by ecological niche model.
Potential distribution maps of *Hy. asiaticum* (A), *D. nuttalli* (B), *D. silvarum* (C), *Hae. longicornis* (D), *Hae. qinghaiensis* (E), *Hae. japonica* (F) and *I. persulcatus* (G) and merged seven tick species (H). Each tick species is indicated in a specific color. The intensity of the color represent the suitable probability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study was supported by the National Key Research Development Program of China (2023YFC2305901, W.-C.C.; 2021YFC2302001, X.-M. C.), and the CAMS Innovation Fund for Medical Sciences (2019-I2M-5-049, W.-C.C.).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.onehlt.2024.100897.

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