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Projected distribution and dispersal patterns of prevalent ticks and tick-borne pathogens in the Sanjiangyuan area of Qinghai province, China, under intense climatic conditions

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Introduction: The Maximum Entropy models (MaxEnt) is commonly employed for early detection of disease transmission, particularly effective in assessing the risk zones and intensity of tick-borne disease transmission based on climatic factors.

Methods: Utilizing the diversity data of common ticks in Qinghai, along with surveillance statistics tick-borne pathogens of ticks and epidemiological information, we have charted and predicted the prevalence of tick and tick-borne pathogens across Qinghai province.

Results and Discussion: The findings indicate that the pivotal environmental factors influencing the distribution of ticks and tick-borne pathogens include land use and land cover (Lucc), elevation (Elev), annual precipitation (Bio12) and annual mean temperature (Bio1). Notably, for *Dermacentor nuttalli*, the significant environmental factors accounted for 35.2% for Lucc, 24.7% for Elev and 18.6% for Bio12. In the case of *Dermacentor silvaru*, the pivotal factors contributed 33.2% for Lucc, 23.7% for Elev and 22.6% for Bio1. For *Haemaphysalis qinghaiensis*, the key environmental variables were 45% for Elev, 30.9% for Lucc and 18.4% for Bio12. Regarding the pathogens, the environmental factors influencing *Borrelia burgdorferi* contributed 61.5% for Lucc, 13.3% for Elev and 11.9% for Bio1. For *Piroplasmida*, the contribution was 62.1% for Lucc, 16.7% for Bio1 and 9.9% for Bio12. *Rickettsia* was influenced by factors accounting for 34.2% for Lucc, 29.7% for Elev and 17.3% for Bio12, while *Anaplasma* variables contributed 38.2% for Bio1, 26.6% for Lucc and 18.9% for Bio12. The finding

indicated that the three predominantly ticks species (*D. nuttalli*, *D. silvaru*, and *H. qinghaiensis*) and the primary tick-borne pathogens (*B. burgdorferi*, *Piroplasmida*, *Rickettsia*, and *Anaplasma*) are predominantly concentrated in the source regions of the Yellow River, the Yangtze River, the Lancang River, and the eastern part of the Haixi Autonomous Prefecture. Projected under the ssp245 scenario, there is a notable expansion trend in the risk areas for ticks and tick-borne pathogens. These findings are consistent with previous epidemiological studies on major ticks and tick-borne diseases in Qinghai conducted by our laboratory, this suggests the feasibility of using the MaxEnt model to predict the distribution of tick-borne disease transmission and compensates for the paucity of research on the Maxent model in the Qinghai Province.

KEYWORDS

MaxEnt model, ticks and tick-borne diseases, latent distribution, transmission risk, environmental impact

1 Introduction

Ticks, belonging to the Ixodida class of arachnids, subsist on the blood of humans and various animals. This parasitic species exhibits a wide range of diversity and has a broad distribution, occupying numerous habitats across the globe. They are notably significant as vectors for the transmission several major infectious diseases, as ranking among all arthropod vectors in terms of importance. It is worth mentioning that ticks feed on a variety of hosts, including birds, mammals, reptiles, and amphibians, and in the process, they transmit pathogens capable of inducing detrimental effects within the host organisms (Estrada-Peña et al., 2012). Such adverse reactions may manifest as skin lesions, allergic responses, edema, disorders of nerve conduction, and can potentially lead to sepsis, abortion, anorexia, metabolic disorders and other severe complications, posing risks to public health and significantly impeding the wellbeing and development of livestock (Han, 2018). The prevalence of ticks and tick-borne diseases is extensive throughout China, affecting public health security significantly due to the nation's diverse climates, complex geographical landscapes, and expansive territories (Zhang, 2012). In recent years, the persistent trend of global warming, coupled with enhanced humidity, has precipitated significant alterations in climate conditions (Zhao et al., 2024). Concurrently, environmental degradation, exacerbated by soil erosion, the contraction of grassland areas, water pollution, and the detrimental effects of invasive alien species, has contributed to a marked decline in biodiversity (Li and Liu, 2002). As a consequence, the structure and function of ecosystems have been modified, which has led to shifts in the density and distribution of vector species, as well as an escalation in the frequency and infection rate of tick-borne diseases across various Chinese provinces and cities. The ongoing reports of tick-borne diseases from Shandong, Henan, Hebei, and Anhui provinces bear witness to the increasing prevalence of these diseases within China (Zhao et al., 2012). Beyond the traditional spectrum of tick-borne illnesses, which includes forest encephalitis, Crimean-Congo hemorrhagic fever, Lyme disease, and spotted fever, a multitude of novel tick-borne infectious diseases have surfaced. Statistics indicate that nearly 40 new tick-borne pathogens have been documented in China since 1982, among which are *B. brucei* (a tick-carried pathogen), a newly identified Bunyavirus, the Alongshan

virus (ALSV), and Human granulocytic anaplasmosis (HGA) (Fang et al., 2015). Tick-borne maladies are highly communicable and pose significant challenges in terms of prompt diagnose and treatment. This is primarily due to the propensity to occur in secluded regions (Shao, 2021). Current scholarly endeavors extensively concentrate on zoonotic pathogens such as *Rickettsia*, *Anaplasma*, *B. burgdorferi*, and *Piriformis*, with the discovery of additional pathogens being reported as research progresses. Beyond examining the impact of these pathogens on human and animal health, there is an intensifying focus on comprehending the interplay between ticks, the pathogens they carry, and their surrounding environment. Investigations have revealed that certain pathogens in a given area tend transported by specific tick species. For instance, *Anaplasma* is predominantly transmitted by the *Amblyomma* spp. and *Ixodes* spp. Ticks, Whereas the primary vectors of *Francisella tularensis* are *D. reticulatus* in Central Europe, and *I. scapularis*, *D. nuttalli* and *D. marginatus* in China (Parola et al., 2005; Gürcan et al., 2006). Research indicates that landforms plays a significant role in the redistribution of water and heat, which is influenced by elevation and slope orientation, consequently impacting the prevalence of ticks and their hosts (Bi et al., 1997). Materna et al. (2008) have demonstrated that altitude is a crucial factor affecting tick distribution density, with regions below 1,000 m above sea level proving more conducive to their proliferation. In a similar vein, Jacobsen (2014) noted that certain landforms on the southern slopes of Montana, United States, offer a particularly suitable environment for *D. andersoni*, likely due to variables such as light intensity, temperature, and snow accumulation. Moreover, temperature and humidity are pivotal in governing both the abundance and activity patterns of ticks (Mysterud et al., 2018). Additional studies have highlighted that variations in climate and environmental conditions can significantly influence tick distribution patterns (Liu, 2021; Liu et al., 2021; Yao et al., 2021).

Qinghai, one of China's highest-altitude provinces, is situated in the northwestern part of country and the northeastern Tibetan Plateau. Characterized by a predominantly plateau landscape, it is interspersed with basins, mountains, and river valleys. The region experiences a continental climate on the plateau, marked by significant temperature fluctuations between day and night, frigid minimum temperatures, intense solar radiation, and sparse, concentrated precipitation. Dominated by animal husbandry, Qinghai is home to a multitude of

domesticated and wild animals, along with a rich, which fosters the survival and proliferation of ticks and their associated pathogens. Moreover, being a key route for migratory birds, Qinghai plays a role in the transmission of tick-borne pathogens, when these birds roost and breed in the province during their migratory period, they act as carriers, potentially disseminating infected ticks and pathogens (Wang et al., 2022). The West Asia migratory route through West Asia, encompassing regions in China includes Qinghai, suggests that migratory birds may potentially serve as agents for the dispersal of ticks and tick-borne pathogens in these territories (Hu et al., 2023). Within the Qinghai region, three predominant tick species, namely, *D. nuttalli*, *D. silvarum*, and *H. qinghaiensis*, are prevalent, predominantly inhabiting grasslands with a primary concentration in the northern parts (Gui et al., 2021; Ma et al., 2023). Moreover, these species act as vectors for several significant pathogens, including *Anaplasma*, *Rickettsia*, *Theileria* spp., and *Babesia* spp. and others, posing a substantial risk to the livestock industry (Zhu et al., 2013; Guo et al., 2021). Thus, due to the above reasons, it is crucial to undertake surveillance efforts and collate data on tick populations and their spatial dissemination. This will enhance our comprehension of the dynamics underlying pathogen transmission, as well as the interplay between vector, pathogen, and the environment.

The ecological niche model discerns the ecological prerequisites of a species by intergrating distribution data with pertinent environmental variables through a specified algorithmic framework. It subsequently projects the findings across diverse spatial and temporal domains to forecast both the actual and potential ranges of the species (Mullins et al., 2011). In contemporary research, ecological niche models have gained extensive application in various fields, including the mapping of invasive species, wildlife conservation, evolutionary biology, assessing the impact of climate change on species distribution and genetic diversity, elucidating the non-random associations between epidemic transmission of infectious diseases and environmental factors, and disclosing transmission patterns as well forecasting transmission risks (Hu et al., 2020). Moreover, ecological niche modeling has been employed to anticipate the likelihood of transmission for zoonotic and parasitic diseases, facilitating the prediction of essential hosts or vectors in disease dissemination and categorizing risks according to the potential extent of distribution (Xing and Hao, 2011). Among the array of modeling tools available, MaxEnt stands out as the preferred choice of researchers due to its superior model precision, user-friendly operation, and straightforward interface (Manel et al., 2001a; Elith et al., 2010). Its independence from thresholds biases and the intuitive nature of its evaluation metric, the area under the curve (AUC) of the receiver operating characteristic (ROC), have contributed to its widespread adoption in model assessment (Liu et al., 2023). For instance, researchers have applied ecological niche modeling to evaluate the suitable habitats of *Ornithodoros* ticks in the Xinjiang Uygur Autonomous Region, identifying temperature as the predominant factor influencing their distribution and predicting an expansion of their suitable zone in the future (Sun et al., 2022). Similarly, ecological niche modeling has been employed to forecast the potential distributional attributes of *H. longhornis*. Findings indicate that factors such as vegetation coverage, precipitation, population density, temperature and animal abundance are picotal environmental elements influencing the geographical spread of *H. longhornis* (He et al., 2022). Beyond *Hyalomma scupense*, investigations utilizing the MaxEnt model suggest that suitable habitats within Xinjiang are likely to expand under

diverse future climate scenarios (Hu et al., 2022). Concurrently, certain studied have emolyed MaxEnt to demonstrate that regions characterized by high levels of precipitation and cooler air temperature are particularly conducive to the habitation of *D. nuttalli* in Xinjiang (He, 2023). Regarding the transmission of zoonotic diseases, the geographical distribution of essential hosts and vectors in the disease's life cycle significantly impacts transmission rates. Ecological demands, including environmental factors, play a crucial role in shaping the disease's distribution. Researchers have applied ecological niche modeling to evaluate the environmental features of suitable habitats, accurately fitting the occurrence of the tick-borne Marpirosis of vector ticks and corroborating the association between *H. anatolicum* and tick-borne Marpirosis, and susceptible animal populations (Niu et al., 2022). These studies have elucidated the intimate connection between the intermediate host and the environment in the transmission of zoonotic disease, enabling a more holistic analysis by incorporating environmental variables. Nonetheless, such research remains inadequate within Qinghai province. There is a pressing need for further investigation into the interplay between ticks, tick-borne pathogens, and environmental factors. Accordingly, this study integrates data on tick-borne biodiversity, surveillance of tick-borne pathogens, and epidemiological information to delineate the distribution and predict the risk of pertinent ticks and tick-borne illnesses in the Sanjiangyuan regions. It aims to evaluate the risk areas and intensity of tick-borne disease transmission, thereby offering a valuable reference for risk analysis and the development of preventive strategies in extreme climate zones.

2 Materials and methods

2.1 Species distribution points

Species distribution data points utilized in the ecological niche modeling were derived from a compilation of extant survey records, specimen documentation, and databases that have been amassed over time. The dataset categorizes into two distinct types: "presence" data and "absence" data. Currently, the most extensively employed category is the "presence" data, as exemplified by the Global Biodiversity Information Facility (GBIF; www.gbif.org) databases (Manel et al., 2001b; Soberón, 2007). For this research, data on the distribution of ticks and tick-borne pathogens were sourced from our laboratory's accumulated field survey data, published scientific literature, and pertinent databases, including the GBIF. In instances where records lacked detailed latitude and longitude information, Google Earth was employed to supplement these data points. To mitigate potential bias in sampling of species distribution data, this study resampled the records at a resolution of 30" within a raster to eliminate duplicates.

2.2 Environment variables and filtering

The selection of environmental variables was primarily informed by the factors that constrain the geographical distribution of ticks and tick-borne pathogens, as well as the intercorrelations among these variables. Access to pertinent

TABLE 1 Environmental variables and sources.

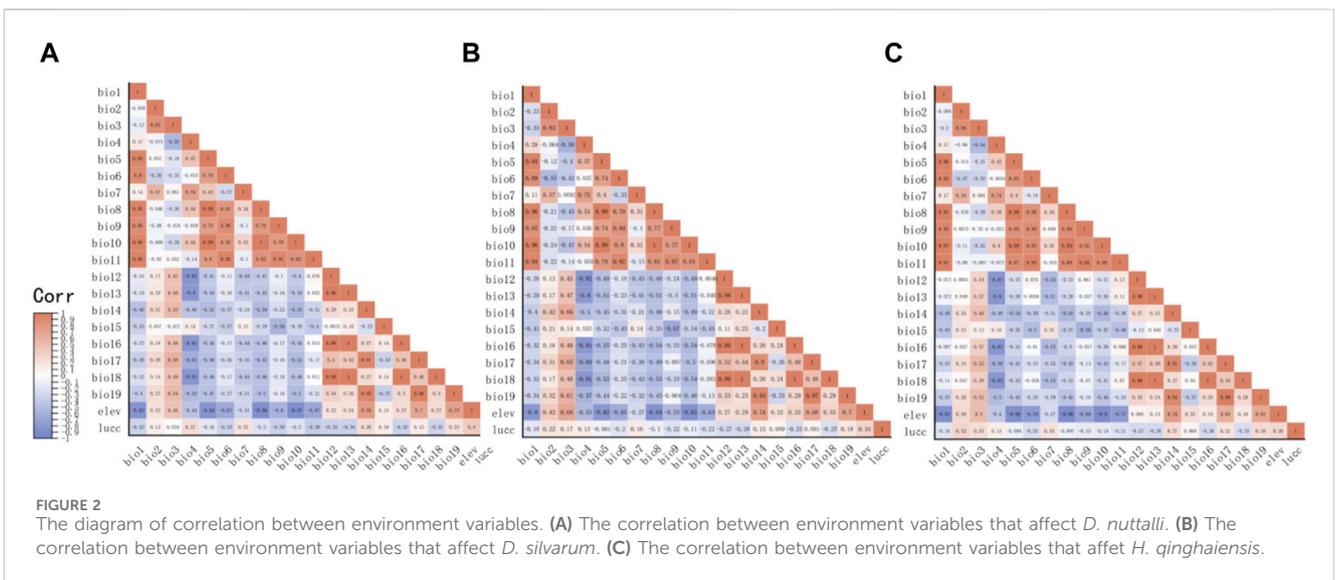
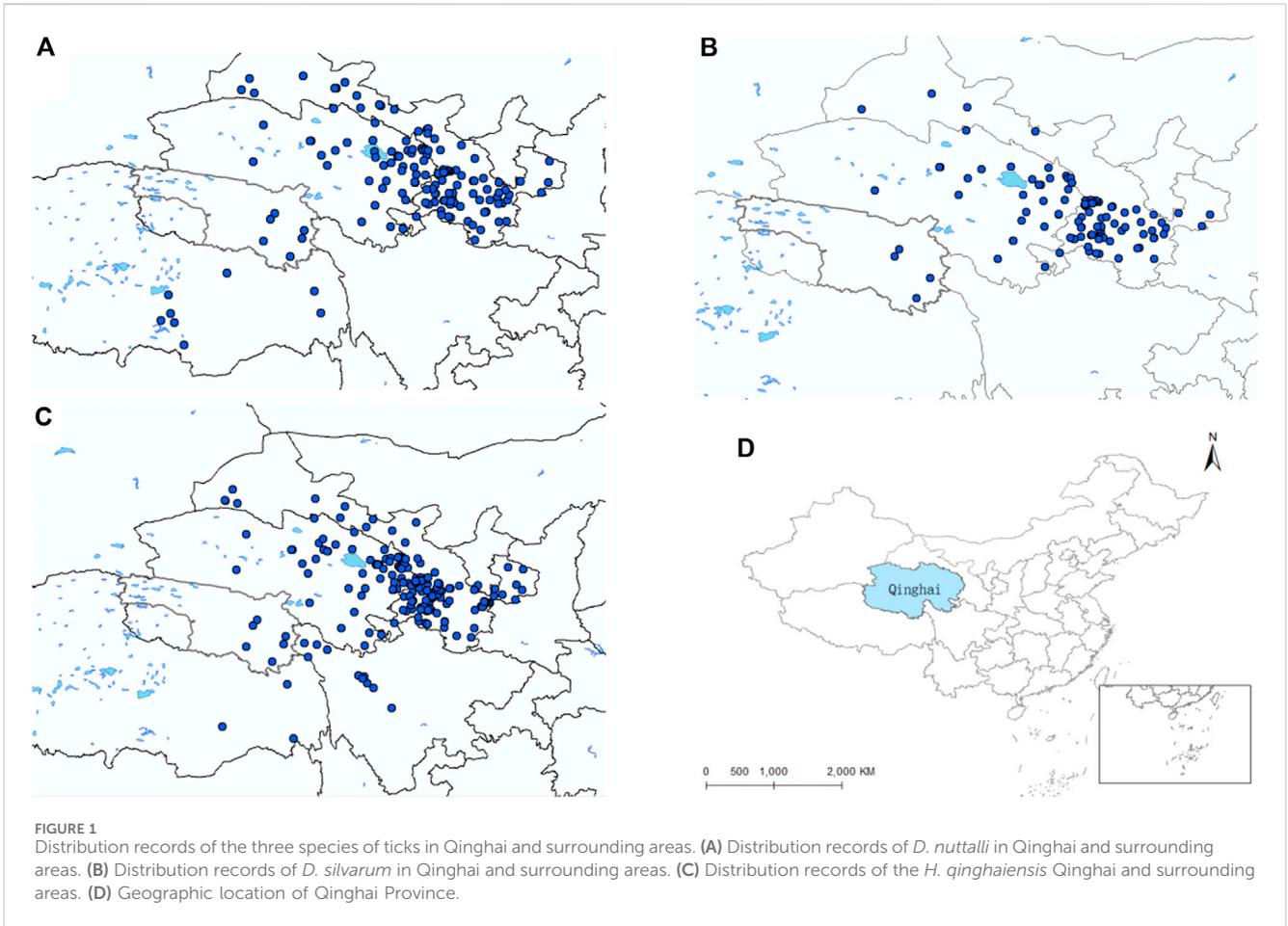
Variable name	Definition	Source
Bio 1	Annual mean temperature	WorldClim
Bio 2	Mean diurnal range [mean of monthly (max temp-min temp)]	WorldClim
Bio 3	Isothermality (Bio2/Bio7)×100	WorldClim
Bio 4	Temperature seasonality	WorldClim
Bio 5	Max temperature of the warmest month	WorldClim
Bio 6	Min temperature of the coldest month	WorldClim
Bio 7	Temperature annual range (Bio 5- bio6)	WorldClim
Bio 8	Mean temperature of the wettest quarter	WorldClim
Bio 9	Mean temperature of the driest quarter	WorldClim
Bio 10	Mean temperature of the warmest quarter	WorldClim
Bio 11	Mean temperature of the coldest quarter	WorldClim
Bio 12	Annual precipitation	WorldClim
Bio 13	Precipitation of the wettest month	WorldClim
Bio 14	Precipitation of the driest month	WorldClim
Bio 15	Precipitation seasonality	WorldClim
Bio 16	Precipitation of the wettest quarter	WorldClim
Bio 17	Precipitation of the driest quarter	WorldClim
Bio18	Precipitation of the warmest quarter	WorldClim
Bio19	Precipitation of the coldest quarter	WorldClim
Elev	Elevation	WorldClim
Lucc	Land use and land cover	https://www.resdc.cn/

TABLE 2 Ranking the percentage contribution and importance of each environmental variable to the model of the three types of ticks (%).

Environment Variables	<i>Dermacentor nuttalli</i>		<i>Dermacentor silvarum</i>		<i>Haemaphysalis qinghaiensis</i>	
	Percent contribution	Permutation importance	Percent contribution	Permutation importance	Percent contribution	Permutation importance
Lucc	35.2	9.1	33.2	10.3	30.9	4.2
Elev	24.7	55.7	23.7	35.8	45	70.5
Bio12	18.6	24.2	16.8	29.7	18.4	19.5
Bio1	18.4	4.4	22.6	20.5	1.3	0.3
AUC	0.941		0.948		0.9366	

variables was sourced from the databases including the China Meteorological Science Data Sharing Service Network (<http://cdc.cma.gov.cn/home.do>), USGS (the U.S. Geological Survey’s Hydro-K data set), Worldclim (<http://www.worldclim.org>), Resource and Environmental Science Data Platform (<https://www.resdc.cn/>). Identifying an appropriate subset of environmental variables from a multitude of datasets is crucial initial step in employing ecological niche models for predictive purposes, with the selection of variables directly influencing the precision of the ultimate predictive outcomes.

As shown in Table 1, in the present research, datasets from 21 species were utilized, derived from the bioclimatic data and elevation data provided by Worldclim and the data of Lucc provided by Resource and Environmental Science Data Platform. At the same time, the classification of Lucc and its meanings were explained in Table 2, Given that these variables are incorporated into the modeling software as geographic layers, their selection necessitates an evaluation of both their biological relevance and geographic patterns they represent (Fan et al., 2019). Variables primarily associated with temperature and



precipitation, such as bio8 and bio9, bio18 and bio19 were initially excluded. Subsequently, the remaining 19 environmental variables were subjected to a correlation

analysis using SDMTtoolbox (Swets, 1988). Ultimately, climate variables with a Pearson correlation value of less than 0.90 were chosen for spatial comparison and the construction of the model.

TABLE 3 Detail of land use types and definition.

Indicator name	Definition
Landcover11	paddy field
Landcover12	rainfed cropland
Landcover21	forest land
Landcover22	shrubwood
Landcover23	sparse forest
Landcover31	high coverage grassland
Landcover32	medium coverage grassland
Landcover33	low coverage grassland
Landcover41	River and canals
Landcover42	lake
Landcover43	reservoir and swag
Landcover44	permanent glacial snow
Landcover45	Intertidal zone
Landcover46	shoaly land
Landcover51	urban land
Landcover52	rural residential area
Landcover53	Other construction land
Landcover61	sand
Landcover62	gobi
Landcover63	saline-alkali soil
Landcover64	swamp
Landcover65	bare land
Landcover66	bare rock stony land
Landcover67	Other unused land (including alpine desert and moss source)
Landcover99	ocean

2.3 Building the model

The map of China and Qinghai Province used in this study are from the Resource and Environmental Science Data Platform (www.resdc.cn/DOI), and this data is provided free of charge by the website, which is derived from “Xu, Xinliang”. Multi-Year Provincial Administrative Boundary Data in China. Resource and Environmental Science Data Registration and Publication System. doi:10.12078/2023010103. The objective underlying the creation of a model is to ascertain the manner in which influencing factors impact the distribution of species, drawing upon established data. This entails the application of mathematical models to generalize or simulate the ecological niche distribution of species based on their known distribution, followed by predictions for hitherto uncharted target areas as informed by the ecological niche requirements derived from training process. In the model’s execution phase, randomly selected distributed data is utilized, with a partition of 75% allocated for model construction, serving as the training dataset, while the remaining 25% reserved for the validation process, function as

the test dataset. The training dataset is instrumental in delineating species distribution, whereas the test dataset is employed to verify the reliability of the predictive outcomes. Subsequently, the MaxEnt model incorporates distribution points of species presence and geographical backdrop data by selecting points where the species is anticipated to be absent within the model’s construction domain. Consequently, the chosen model construction (Zhu and Qiao, 2016).

2.4 Model evaluation

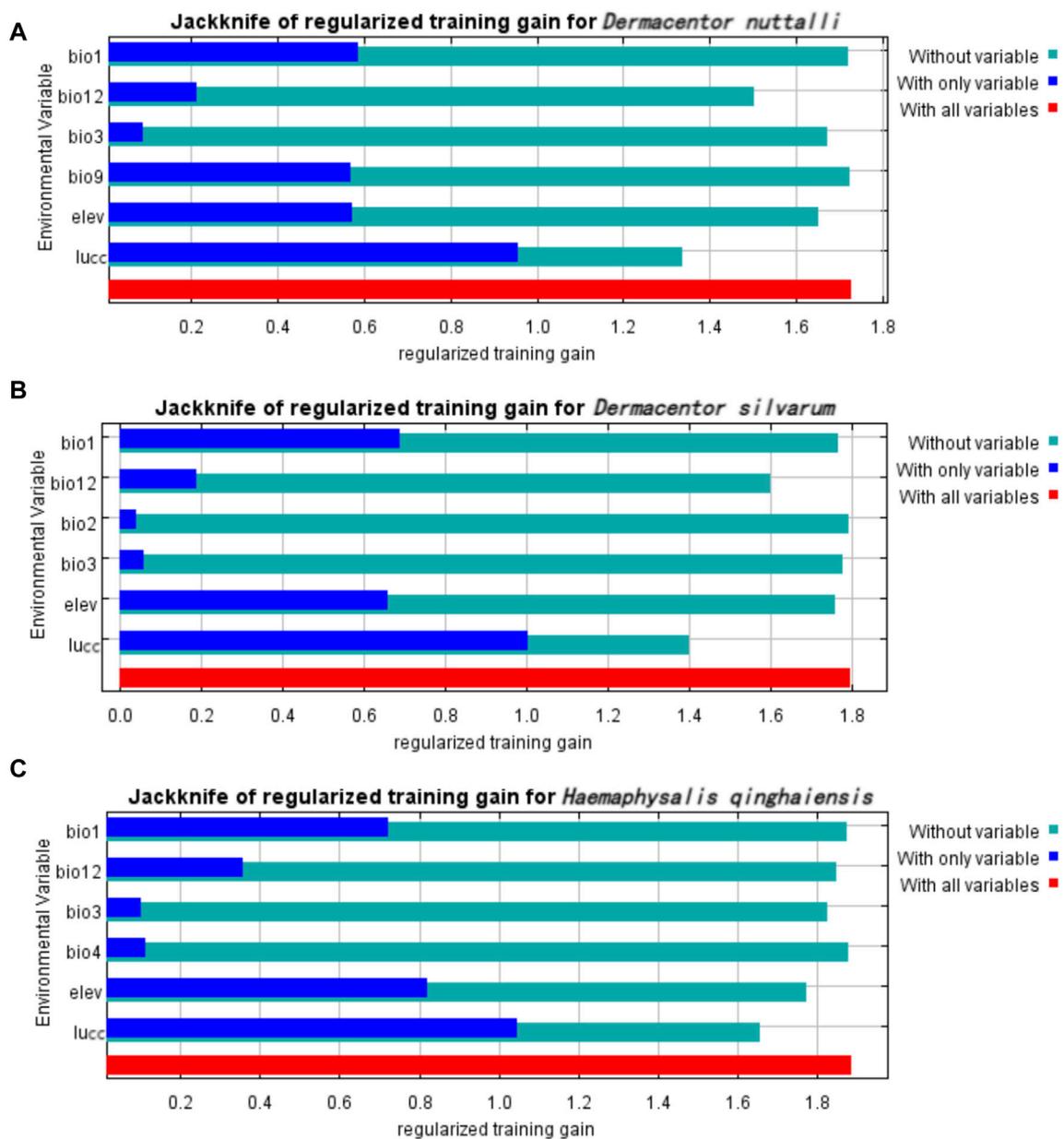
Model assessment and validation are pivotal step that ascertain the credibility of model predictions within the application process. Typically, evaluation metrics for models encompass accuracy, sensitivity, specificity, kappa statistic, True Skill Statistic (TSS), and the Area Under the Curve (AUC). Notably, the AUC is the sole metrics unaffected by the model’s prediction threshold, enabling an assessment of the model the need to define a threshold. MaxEnt models are developed with an analysis of the Receiver Operating Characteristic (ROC) curve, which serves to authenticate the model’s dependability, and this is conducted in tandem with the model construction. Additional validation can be achieved through the use of a completely independent dataset, subject to a secondary ROC analysis. The predictive outcomes were appraised using 25% of test data points, with model assessment conducted via the ROC curve. ROC curve analysis is extensively employed in evaluating the performance of medical diagnostic tests and, in recent times, has been extended to the assessment of species distribution prediction models. Its advantage lies in its ability to gauge the accuracy of the prediction model using AUC values, without being constrained by threshold settings (Liu et al., 2011). The area under the curve (AUC) serves as an index of the model’s predictive accuracy, with value ranging from 0 to 1. A higher AUC value signifies stronger model discrimination. Typically, AUC values between 0.5 and 0.7 are considered low, 0.7 to 0.9 as moderate, and values above 0.9 as high (Brown et al., 2017). In an ideal scenario, the model’s predicted range would coincide precisely with the species, resulting in an AUC of 1.

2.5 Predictor variable influence analysis

MaxEnt allows for simultaneous knife-cut analysis of the contribution of variables to the modeling process and build response curves for each variable, thus indirectly reflecting the influence of each variable on the species distribution. In addition, the above results can be further analyzed and projected in relation to future changes in environmental variables.

2.6 Classification of climate suitability

The habitat suitability index for ticks and their tick-borne pathogens was determined through the application of the MaxEnt model. A higher index value indicates a more profound environmental adaptation by the species, with the scale ranging from 0 to 1, also referred to as the risk value. In conjunction, the SDMTools module within the ArcGIS 10.8 software suite was utilized to delineate the extent of each suitable habitat area. The tick risk index was classified into five distinct risk levels by



Note: bio1 Annual mean temperature; bio3 Isothermality(Bio2/Bio7) × 100; bio4 Temperature seasonality; bio12 Annual precipitation; elev Elevation; lucc Land use and land cover.

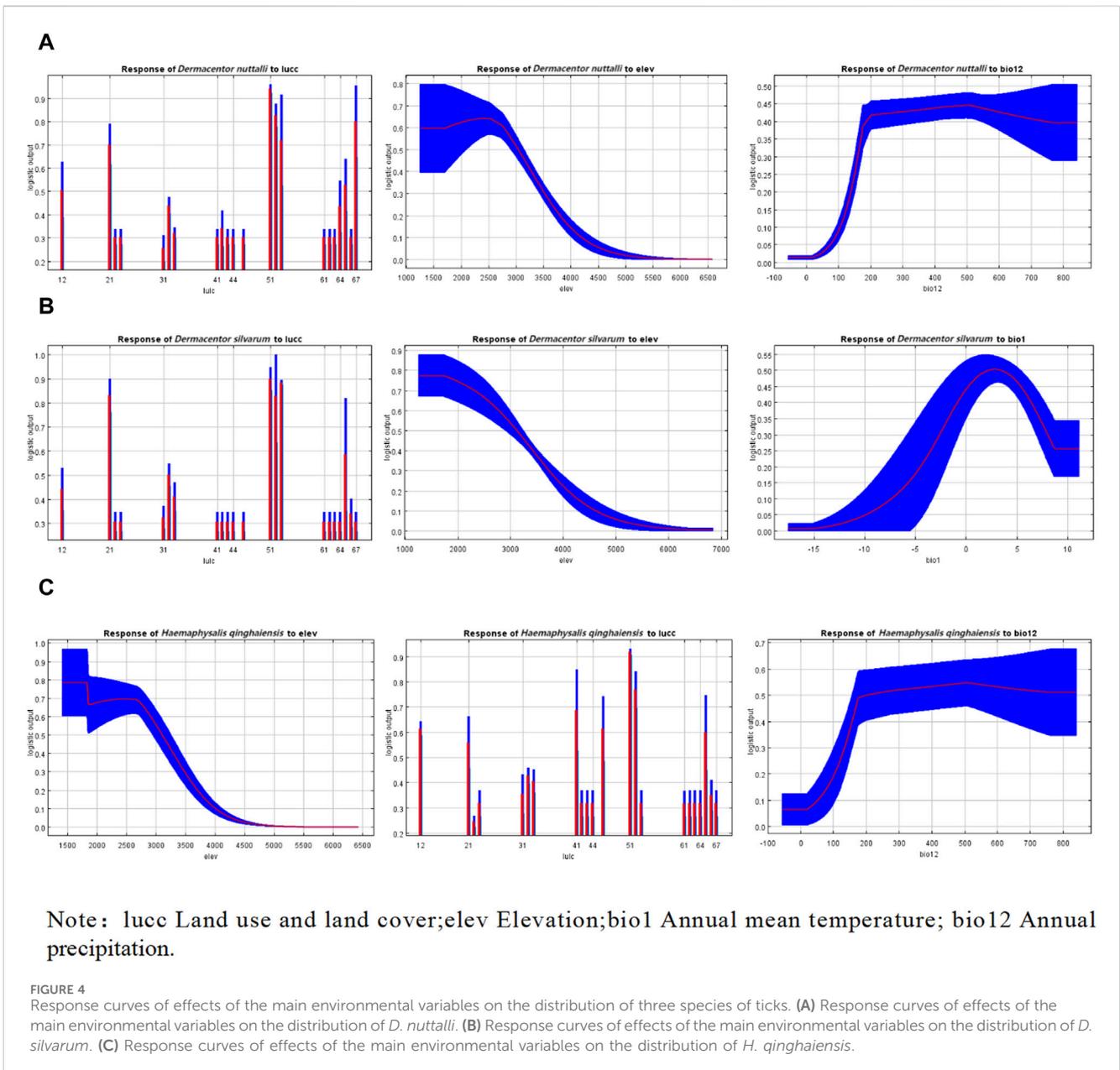
FIGURE 3 Jackknife test results of the environmental factors affecting the distribution of three species of ticks. (A) Jackknife test results of the environmental factors affecting the distribution of *D. nuttalli*. (B) Jackknife test results of the environmental factors affecting the distribution of *D. silvarum*. (C) Jackknife test results of the environmental factors affecting the distribution of *H. qinghaiensis*.

employing the “Jenks’ natural breaks” method for reclassification, distinguishing between high, medium, medium-low risk areas, and those free from risk.

2.7 Climate change impact analysis

In anticipation of future projections, we employed the CIMP6 annual dataset, which aligns with the Chinese future

climate scenario and integrates crucial components such as atmospheric, land surface, oceanic, and sea ice models. Specifically, we focused on the spp245 scenario under the BCC-CSM2-MR model (Wu et al., 2019; Xin et al., 2019). This dataset was sourced from the WorldClim environmental database (https://www.worldclim.org/data/cmip6_clim30s). To assess prospective land use and land cover (Lucc) scenarios, we referred to Zhang’s investigation, which factors in the implications of future climate change and socio-economic evolution, alongside analogous



simulations from the preceding year. Additionally, we selected the ssp 245 scenario model, recognized for its commendable simulation accuracy (Zhang et al., 2023).

3 Result

3.1 Risk assessment of the occurrence of three tick species in the Qinghai

Through the collation of the gathered data, we have secured original records of distribution of the *D. nuttalli*, *D. silvarum* and *H. qinghaiensis* in Qinghai and its surrounding regions (Supplementary Materials S1–S3). As depicted in Figures 1A–C, this data is displayed on the map. The geographical position of Qinghai in China is shown in Figure 1D. The eventual predictive

outcomes are contingent upon the selection of environmental variables, making the choice of predictor variables a pivotal step in the application of ecological niche models. We conducted a correlation analysis to meticulously select climate variables with a Pearson correlation value below 0.90 for spatial evaluation and model construction, as illustrated in Figure 2. The MaxEnt algorithm employed a Jackknife procedure, systematically eliminating each variable to assess its contribution and importance to the model, ranking them as indicated in Table 3.

Our observations from Table 3 reveal that the predominant factors influencing the distribution of the three tick species are Lucc, elevation, and bio12, each with varying degrees of importance as detailed in the table, The Jackknife test results, presented in Figure 3, quantify the contribution of each variable to the model. The blue bar represents the model’s efficacy when the variable is considered in isolation, while the green bar signified the model’s performance in

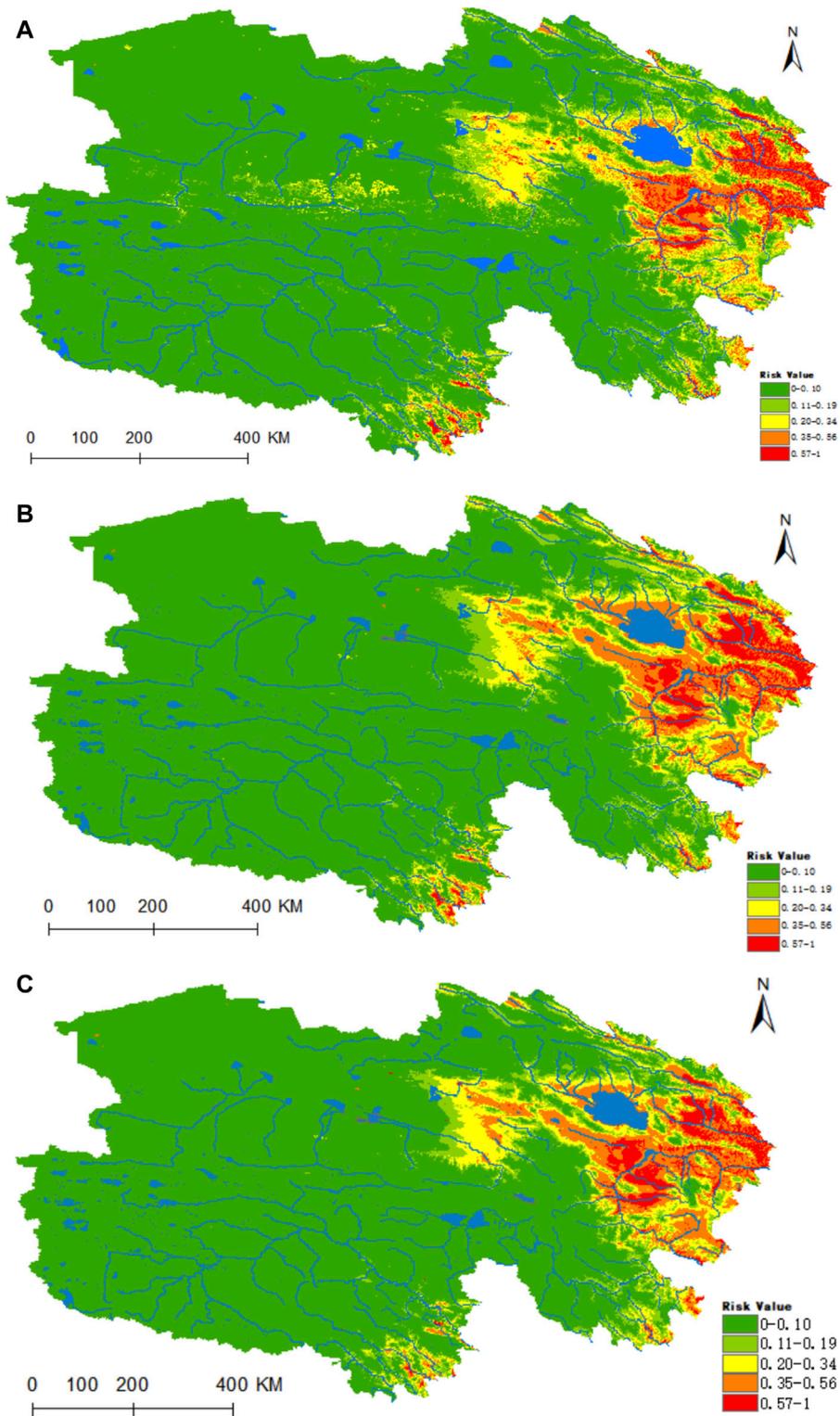


FIGURE 5 Predicted distribution and trends in distribution of *D. nuttalli* in Qinghai. (A) Current potential distribution of *D. nuttalli* in Qinghai. (B) Distribution of *D. nuttalli* in Qinghai under the ssp245-2050 scenarios. (C) Distribution of *D. nuttalli* in Qinghai under the ssp245-2070 scenarios.

the absence of that variable. Notably, Lucc emerges as the variable with the highest gain when utilized as the sole environmental factor in simulations (Figure 3).

In the depicted response curve plot, the vertical axis represents the probability of occurrence, while the horizontal axis indicates the specific values of the environmental variable.

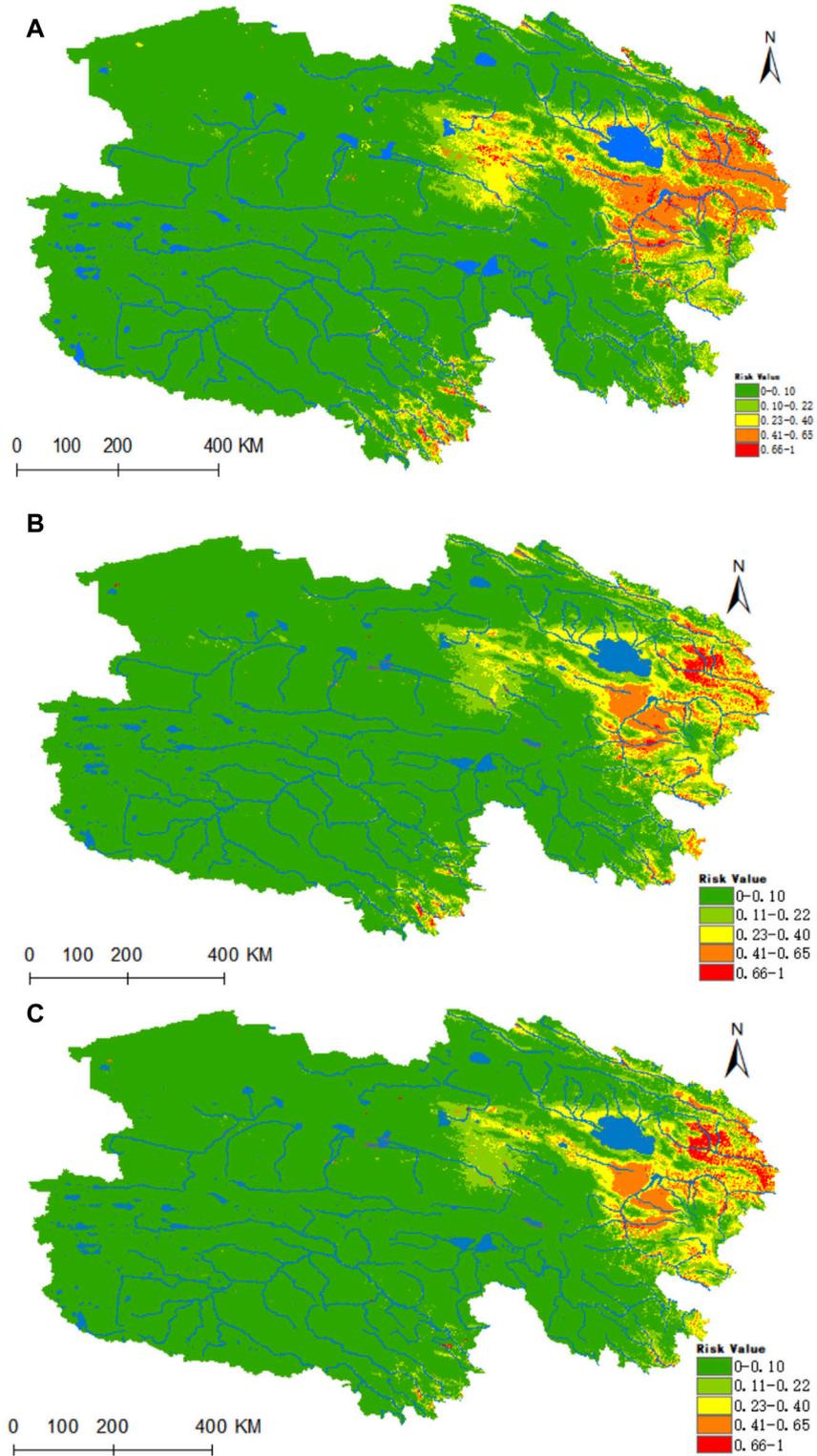


FIGURE 6
 Predicted distribution and trends in the distribution of *D. silvarum* in Qinghai. (A) Current potential distribution of *D. silvarum* in Qinghai. (B) Distribution of *D. silvarum* in Qinghai under the ssp245-2050 scenarios. (C) Distribution of *D. silvarum* in Qinghai under the ssp245-2070.

As illustrated in Figure 4, a notable increase in the probability of occurrence is observed for the three tick types as the land use and land cover categories shift to types 51 and 67, succeeded by type

21. These categories correspond to urban land, other unused land, and forested land, respectively. Specifically, for *H. qinghaiensis*, a high likelihood of occurrence is evident in

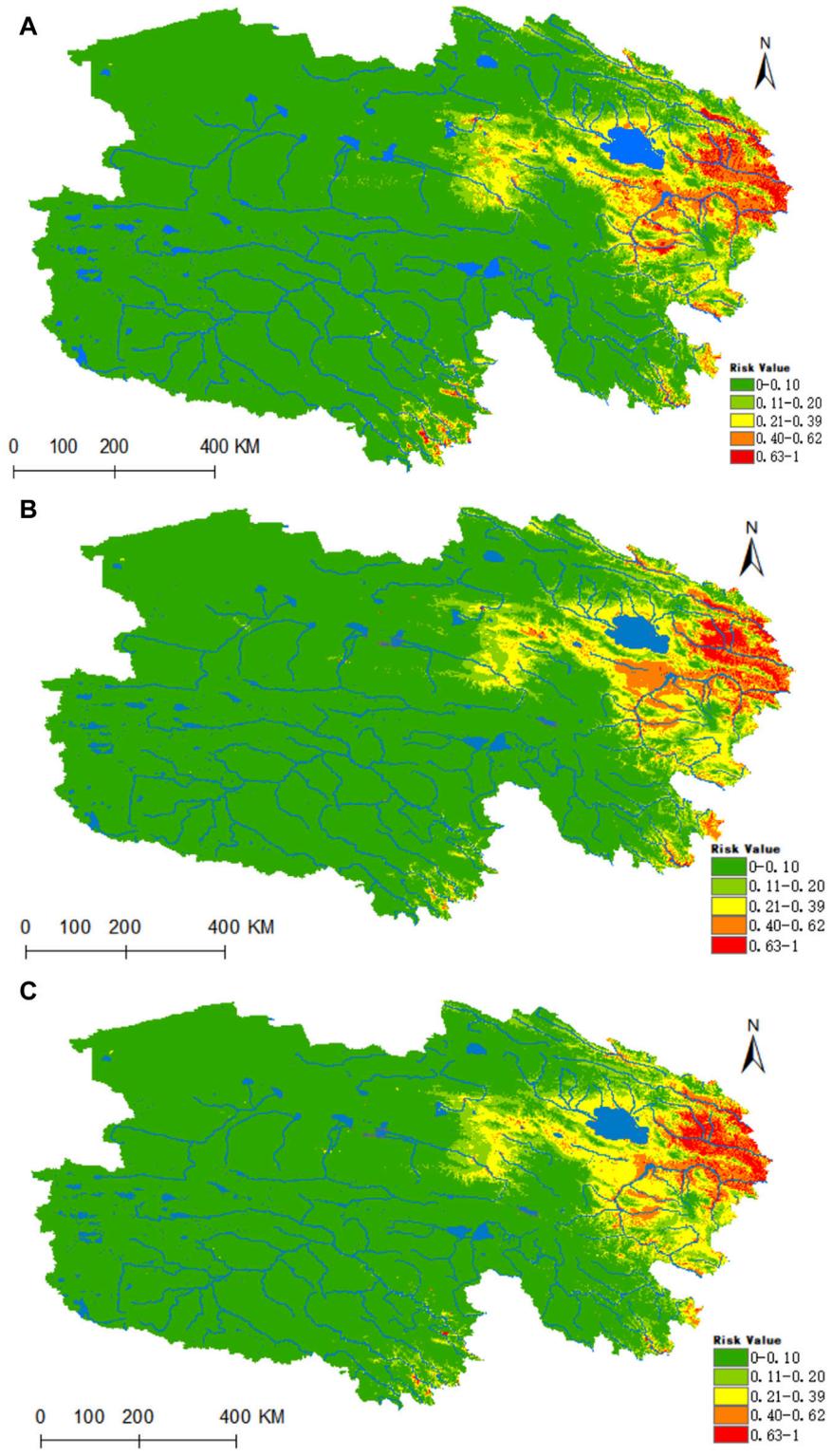
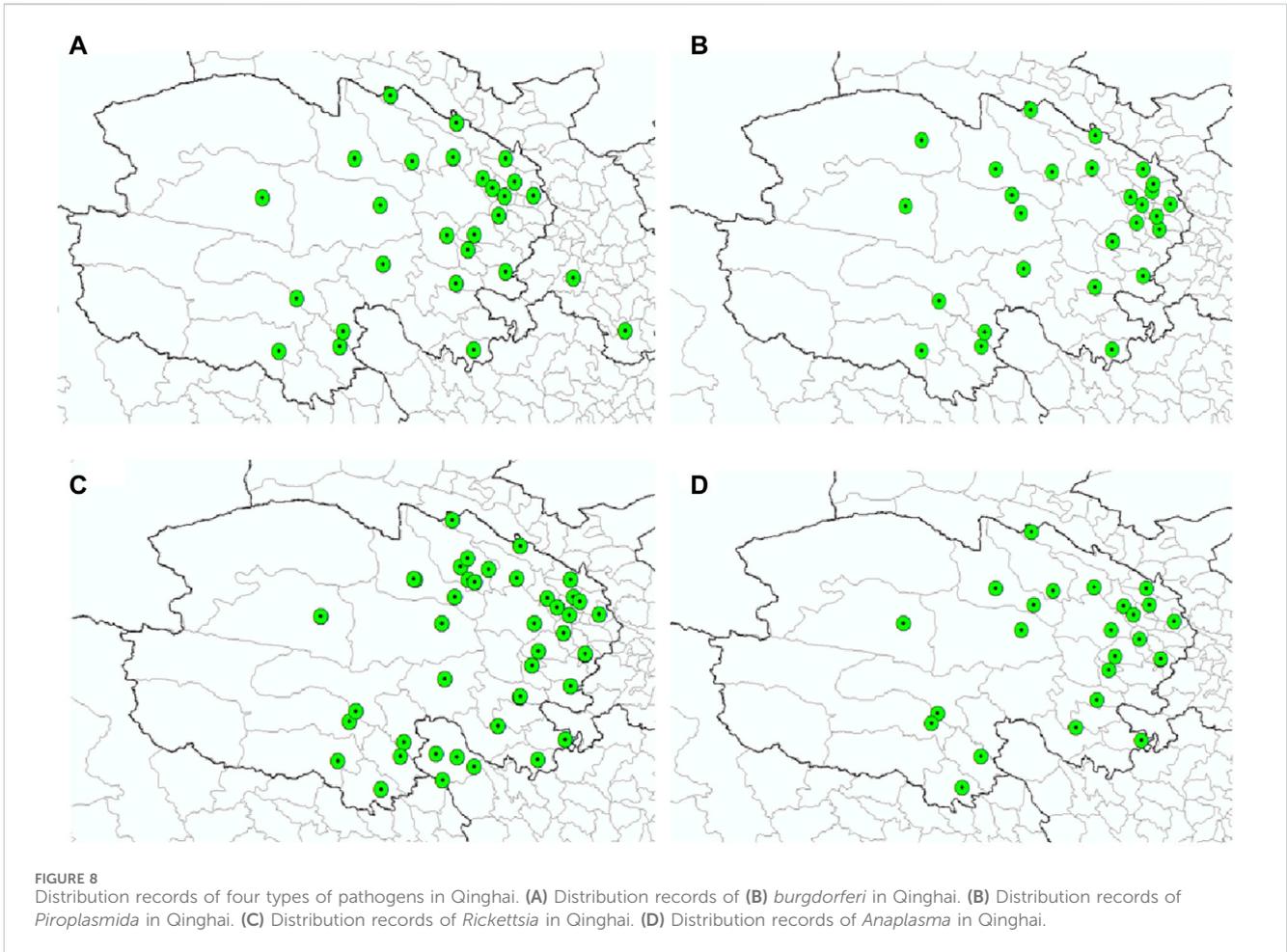


FIGURE 7
 Predicted distribution and trends in the distribution of *H. qinghaiensis* in Qinghai. **(A)** Current potential distribution of *H. qinghaiensis* in Qinghai. **(B)** Distribution of *H. qinghaiensis* in Qinghai under the ssp245-2050 scenarios. **(C)** Distribution of *H. qinghaiensis* in Qinghai under the ssp245-2070.

41 and 65 land types, which are characterized as canals and bare land, respectively. Furthermore, the probability of occurrence for these tick types increases with elevation, reaching its peak at

2,500 m, 571.4–1,571 m, and 1258–1709.6 m, respectively. Regarding *D. nuttalli* and *H. qinghaiensis*, their occurrence probability also escalates with the rise in annual precipitation,



with the highest likelihood observed at approximately 500 mm, as depicted in Figure 4.

The map's findings revealed that the regions highly conducive to the habitation of *D. nuttalli* are predominantly concentrated in the eastern portion of Qinghai, the Hainan Autonomous Prefecture, the Huangnan Autonomous Prefecture, the eastern sector of Haixi Autonomous Prefecture, as well as the river valleys of Yushu and Guoluo (refer to Figure 5). presently, under prevailing climatic conditions, the areas designated as high risk, medium risk, medium-low risk, low risk, and non-risk for *D. nuttalli* amount to 0.1762×10^6 , 0.3856×10^6 , 0.4868×10^6 , 0.4958×10^6 and 5.3932×10^6 km², respectively. In the context of the ssp245 future scenario, a notable enhancement in the habitat suitability within the Hainan Autonomous Prefecture is predicted (refer to Figures 5B,C). Utilizing the ArcGIS 10.8 software, we calculated the extent of each suitability category, and the results indicated that by the year 2050, under the ssp245 scenario, there will be a 22% augmentation in the high-risk zone, a 33.4% enlargement in the medium-risk zone, a 7.6% reduction in the medium-low risk areas, a 4.9% decrease in the low-risk regions, and a 2% contraction in the non-suitable zones. In the climate projection for 2070, the high-risk area is expected to expand by 3.7%, with a substantial increase of 31.4% projected for the medium-risk zone.

Figure 6 illustrates that the highly suitable zones for *D. silvarum* are predominantly situated in the eastern portion of

Qinghai, with the eastern regions of Haixi and Hainan Autonomous Prefectures, Huangnan Autonomous Prefecture, as well as the river valleys of Yushu and Guoluo, being predominantly classified as moderately suitable (Figure 6A). Under the prevailing climatic conditions, the areas designated as high risk, medium risk, medium-low risk, low risk, and non-risk for *D. silvarum* amount to 0.0523×10^6 , 0.3538×10^6 , 0.4361×10^6 , 0.5911×10^6 and 5.5044×10^6 km², respectively. According to the ssp245 scenario model, the distribution of *D. silvarum* is forecast to be primarily concentrated in the eastern Qinghai Province in both the years 2050 and 2070, with a notable increase in the high-risk zone, expanding by 13% and 21% respectively.

Figure 7A reveals that *H. qinghaiensis* is predominantly distributed in the eastern part of Qinghai, with an elevated presence in the eastern Haixi Autonomous Prefecture, as well as in the Yushu and Guoluo River Valley. In the current climate, the regions classified as high risk, medium risk, medium-low risk, low risk, and non-risk for *H. qinghaiensis* are 0.101×10^6 , 0.2406×10^6 , 0.508×10^6 , 0.4837×10^6 and 5.6044×10^6 km², respectively. Under the projected climate models, the high-risk zone for this tick species remains concentrated in the eastern Qinghai Province, while the medium-risk area experiences a notable increase of 16% in the 2050 period, as depicted in Figures 7B,C.

TABLE 4 Contribution and importance ranking of each environmental variable to the model (%).

Environment Variables	<i>Borrelia burgdorferi</i>		<i>Piroplasmida</i>		<i>Rickettsia</i>		<i>Anaplasma</i>	
	Percent contribution	Permutation importance	Percent contribution	Permutation importance	Percent contribution	Permutation importance	Percent contribution	Permutation importance
Lucc	61.5	24.6	62.1	20.6	34.2	11.3	26.6	11.4
Elev	13.3	37.1	8.9	38.1	29.7	45.6	8.9	44.3
Bio12	11.3	22.2	9.9	16.9	17.3	36.9	18.9	19.1
Bio1	11.9	13.7	16.7	15.4	12.1	1.4	38	16.6
AUC	0.9332		0.9253		0.933		0.954	

3.2 Risk assessment of the occurrence of four tick-borne diseases in the Sanjiangyuan region of Qinghai

Figure 5 delineates the documented distribution of four tick-borne pathogens-*B. burgdorferi*, *Piroplasmida*, *Rickettsia* and *Anaplasma*-across Qinghai and its environs. This illustration is based on a comprehensive analysis of our laboratory’s years of survey data, augmented by a thorough literature review. Independently, we have gathered 52 distribution records for *B. burgdorferi* (Figure 8A), 52 for *Piroplasmida* (Figure 8B), 276 for *Rickettsia*, and 100 for *Anaplasma* within the Qinghai region and its periphery (Figures 8C,D). These original data as shown in Supplementary Materials S4–S7.

According to Table 4, the principal factors influencing the distribution of these tick-borne pathogens are Land use and Land cover (Lucc), elevation (bio12), and bioclimatic variable bio1, each with varying degrees of importance as detailed in Table 4.

Figure 9A reveals that the areas highly conducive to *B. burgdorferi* are concentrated in the eastern part of Qinghai, with the valleys of the Yellow River, Yangtze River source, and Lancang River source in southern Qinghai being of medium suitability. Presently, the areas designated as high, medium, medium-low, low, and non-risk for *B. burgdorferi* infection encompass 0.1095×10^6 , 0.2704×10^6 , 0.5227×10^6 , 0.8225×10^6 , and 5.212×10^6 km², respectively. Projecting into the future using climate models for the years 2050 and 2070, there is a notable increase in habitat suitability in the Haixi Autonomous Prefecture, as well as the Yangtze and Yellow River valleys in southern Qinghai (Figures 9B,C). In both scenarios, the high-risk areas for *B. burgdorferi* expand by 76% and 95%, while the medium-risk areas increase by 74% and 75%.

Figure 10 illustrates that the regions highly conducive to *Rickettsia* are predominantly concentrated within the Haixi Autonomous Prefecture. The areas designated as high, medium, medium-low, low risk, and non-risk for *Rickettsia* were found to be 0.2178×10^6 , 0.3641×10^6 , 0.5132×10^6 , 0.6653×10^6 , and 5.1773×10^6 km², respectively. Projecting into the 2050 period under the ssp245 scenarios, a notable enhancement in habitat suitability is anticipated for the Yangtze River headwaters and Lancang River headwaters valley zones in the southern Qinghai region, marked by a substantial increase of 96% in the high-risk area and a moderate upsurge of 24% in the medium-risk zone.

Figure 11 reveals that the highly suitable habitat for *Piroplasmida* is primarily located in the eastern part of Qinghai, encompassing the source area of the Yellow River and the eastern sector of the Haixi Autonomous Prefecture, in contrast to the Yangtze River source area (Figure 10A). Within the prevailing climatic conditions, the areas of high, medium, medium-low, low risk, and non-risk for *Piroplasmida* were estimated to be 0.1296×10^6 , 0.3403×10^6 , 0.7389×10^6 , 0.111×10^6 , and 4.6186×10^6 km² respectively. Furthermore, under the future climate projections for the 2050 and 2070 periods based on the ssp245 scenarios, a significant expansion is expected in the suitability of the Yangtze River headwaters, Lancang River headwaters valley zones, and the Haixi Autonomous Prefecture in the eastern Qinghai region. By the 2070 period, the areas of high,

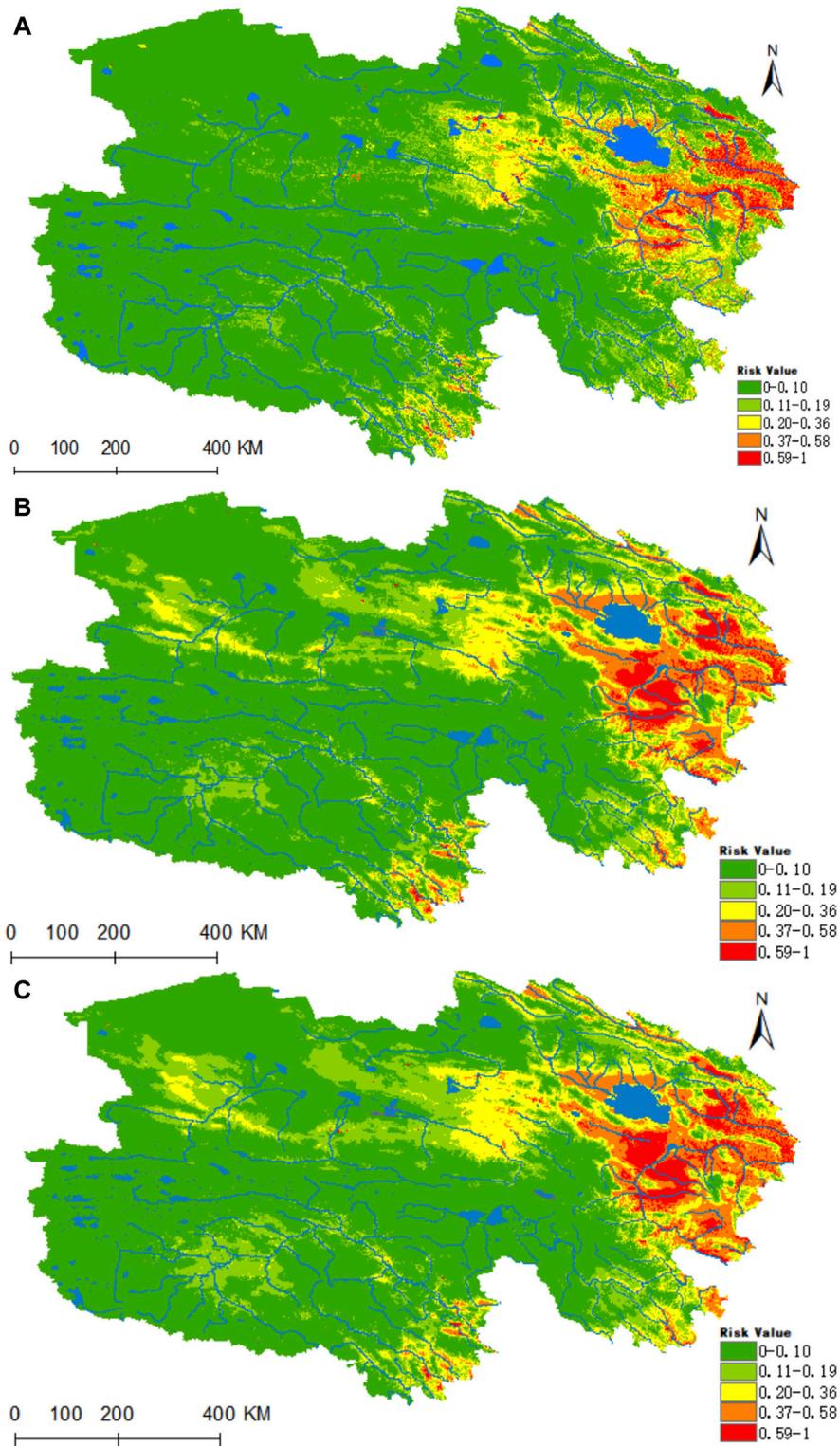


FIGURE 9 Analysis of the fitness zones and trends in the distribution of *B. burgdorferi* in Qinghai. (A) Current potential distribution of *B. burgdorferi* in Qinghai. (B) Distribution of *B. burgdorferi* in Qinghai under the ssp245-2050 scenarios. (C) Distribution of *B. burgdorferi* in Qinghai under the ssp245-2070.

medium, medium-low, and low suitability are projected to increase by 67.5%, 62.6%, 7.2%, and 5.4%, respectively.

Ultimately, the model depicted in Figure 12A identifies the highly suitable zone for *Anaplasma* as predominantly concentrated in the

source region of the Yellow River, located in eastern Qinghai, and also distributed at the upper reaches of both the Yangtze and Yellow Rivers in southern Qinghai. Under the prevailing climatic conditions, the areas of high, medium, medium-low, low, and non-risk for

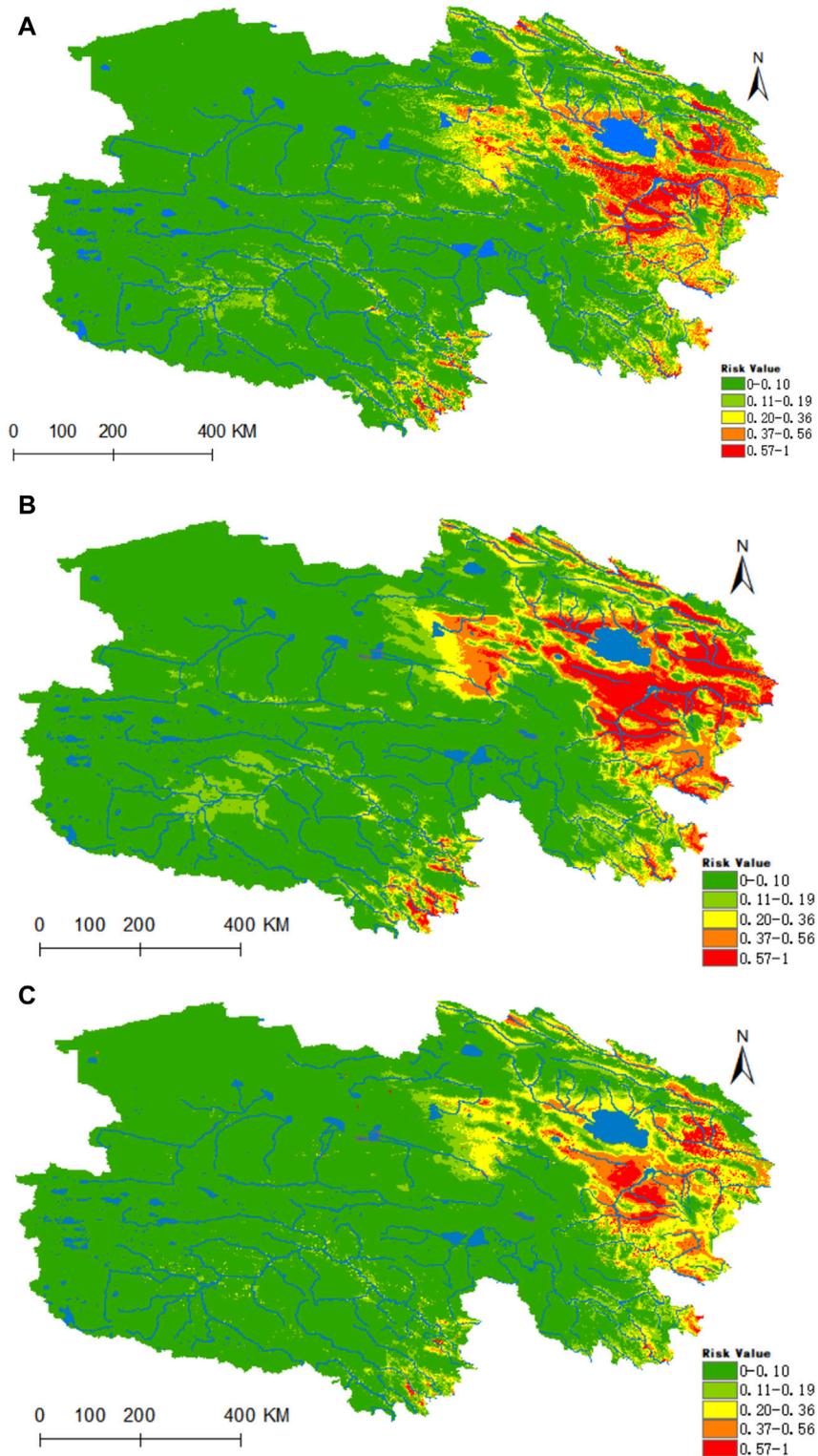


FIGURE 10 Analysis of the fitness zones and trends in the distribution of *Rickettsia* in Qinghai. (A) Current potential distribution of *Rickettsia* in Qinghai. (B) Distribution of *Rickettsia* in Qinghai under the ssp245-2050 scenarios. (C) Distribution of *Rickettsia* in Qinghai under the ssp245-2070.

Anaplasma are estimated at 0.2151×10^6 , 0.3475×10^6 , 0.5682×10^6 , 0.4554×10^6 , and 5.3515×10^6 km² respectively. In the time frames of 2050 and 2070, under the ssp245 scenarios, the habitat suitability for *Anaplasma* is projected to decrease substantially within Qinghai (as

shown in Figures 12B,C). Nonetheless, a notable level of risk is expected to persist in the source areas of the Yellow River in eastern Qinghai, as well as in the headwaters of the Yangtze and Yellow Rivers in southern Qinghai.

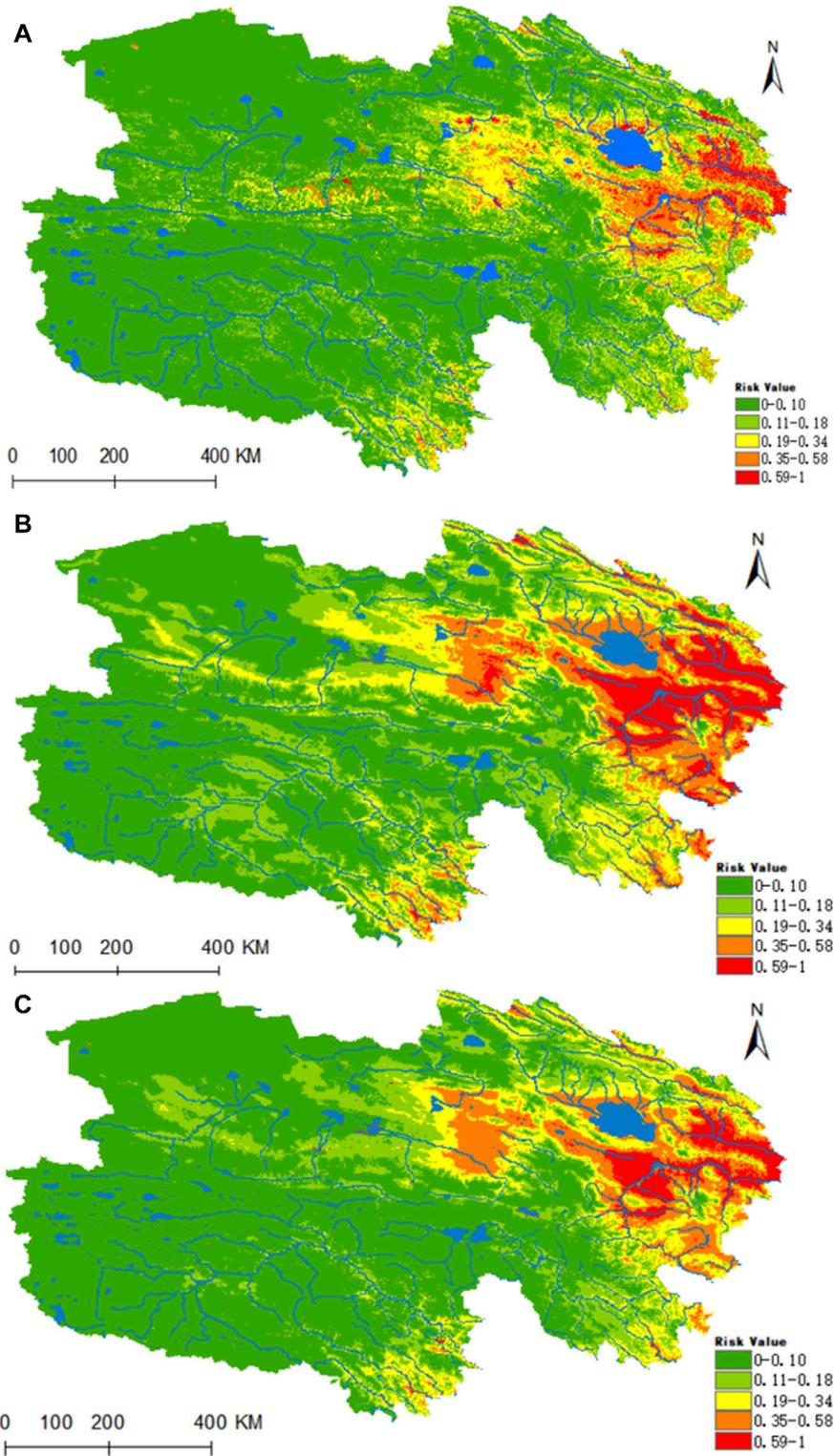


FIGURE 11 Analysis of the fitness zones and trends in the distribution of *Piroplasmida* in Qinghai climate change. (A) Current potential distribution of *Piroplasmida* in Qinghai. (B) Distribution of *Piroplasmida* Qinghai under the ssp245-2050 scenarios. (C) Distribution of *Piroplasmida* in Qinghai under the ssp245-2070.

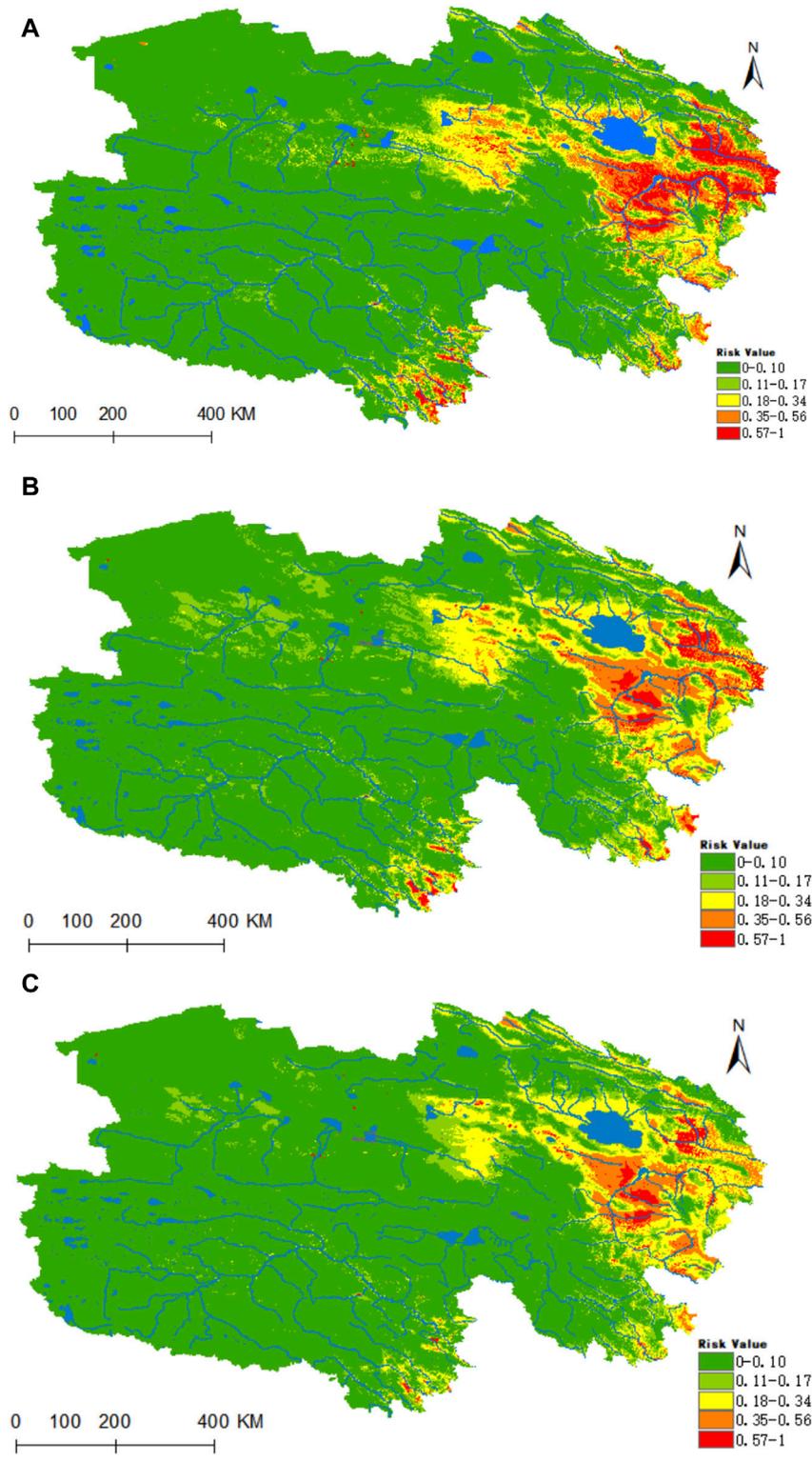


FIGURE 12 Analysis of the fitness zones and trends in the distribution of *Anaplasma* in Qinghai climate change. (A) Current potential distribution of *Anaplasma* in Qinghai. (B) Distribution of *Anaplasma* Qinghai under the ssp245-2050 scenarios. (C) Distribution of *Anaplasma* in Qinghai under the ssp245-2070.

4 Discussion

In this study, both ticks and tick-borne pathogens were subjected to a simulation of 10 iterations, with all model AUC

values exceeding 0.9. It is particularly noteworthy that the MaxEnt model exhibited an exceptional simulated efficacy. The research findings suggest that the three varieties of ticks and their associated pathogens are predominantly distributed across the

eastern and southern regions of Qinghai Province, which is the source of the Yellow River, the Yangtze River, and the Lancang River, collectively known as Sanjiangyuan. This distribution pattern enables the prediction of potential species distribution and forecasting of future distributions at the environmental level. Additionally, correlation analysis identified Lucc, elev, bio1, and bio12 as the most influential variables in the modeling process. Specifically, the infestations of the three tick species were found to be more prevalent in urban areas, rural habitations, barren land, riverine channels, and forested regions. Moreover, an inverse correlation was observed with increasing elevation beyond 2,500 m, resulting in a decreased likelihood of encountering ticks. This study employed SDMtools to delineate risk areas and to compare the ranges of suitable habitats under current environmental conditions with those projected for the years 2050 and 2070, within the ssp245 scenario. The outcomes indicate that, with the exception of *Anaplasma*, the suitable ranges for the three tick species and their tick-borne pathogens are generally trending towards expansion. It is pertinent to highlight that the outcomes of simulating various species using different climate and geographical datasets do exhibit variations (Ying et al., 2016). However, employing MaxEnt for simulating species' geographical distribution remains a pivotal research methodology (Zhu et al., 2017).

Although ticks are specialized blood-sucking ectoparasites and serve as vector organisms, they lead a majority of their life cycle as free-living creatures in nature (de la Fuente et al., 2017; Liu, 2018). Consequently, variations in temperature and humidity significantly impact the life cycle of these ticks (Wardhana et al., 2014; Leal et al., 2020). Within a specific range, an increase in temperature and humidity can expedite the development process of ticks, thereby shortening their life cycle (Yao and Chen, 1981). In the model under consideration, the prolonged and frigid winters in Qinghai may explain the substantial influence of temperature on the distribution of tick species. At sub-zero temperatures, body fluids within ticks can crystallize into ice, causing damage (Dautel and Knülle, 1996; Dörr and Gothe, 2001). species such as *D. nuttalli*, *D. silvarum*, and *H. qinghaiensis*, which are all triple-hosted ticks, devote 90% of their life cycles to seeking a host (Bai et al., 1999; Yuan et al., 2002). Ticks typically position themselves atop vegetation to await a host, descending to the undergrowth periodically to absorb moisture, as the dry atmosphere can lead to dehydration and subsequent death (Lauterbach et al., 2013). However, within an optimal humidity range, ticks can remain for extended periods at the summit of plant, awaiting the passage of a potential host (Wright and Machin, 1990). Conversely, excessive humidity results in dew formation on plant surfaces, which hinders tick movement (Heath, 2016). Conversely, excessive humidity results in dew formation on plant surfaces, which hinders tick movement (Piao et al., 2004). Given that ticks must ascend to the heights of vegetation in search of a host and descend for moisture, land use and land cover emerge as critical factors influencing their distribution. Consequently, *D. nuttalli*, *D. silvarum*, and *H. qinghaiensis* are primarily distributed in regions of Qinghai Province with favorable temperature and humidity conditions.

The limitations of this investigation were demarcated as follows. Initially, the sites acquired do not comprehensively represent all potential locations. Secondly, beyond the direct transmission of pathogens among ticks, between ticks and hosts, and among hosts themselves, the possibility of indirect transmission between ticks and other vector species poses a formidable challenge. This complexity makes it difficult to accurately predict the risk of pathogen dissemination, a task that involves a multitude of variables. The spatial distribution forecasts of ticks and their associated tick-borne pathogens within at-risk zones, as provided by this study, are expected to enhance sampling strategies, reduce the incidence of random sampling, and thereby conserve both time and financial resources. Furthermore, these predictions stand to significantly contribute to the prophylactic measures and management of tick-borne diseases, while also enriching the research on the predominant tick species in Qinghai Province.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#), further inquiries can be directed to the corresponding author.

Ethics statement

The animal study was approved by the institutional Animal Care and Use Committee of Qinghai University. The study was conducted in accordance with the local legislation and institutional requirements. Ethics approval number: SL-2023005.

Author contributions

LX: Conceptualization, Data curation, Investigation, Methodology, Software, Writing—original draft. YG: Conceptualization, Data curation, Investigation, Methodology, Resources, Software, Supervision, Writing—review and editing. LY: Data curation, Investigation, Methodology, Resources, Writing—review and editing. ZL: Investigation, Project administration, Resources, Supervision, Writing—review and editing. MK: Investigation, Project administration, Resources, Supervision, Writing—review and editing. XHa: Investigation, Resources, Supervision, Writing—review and editing. CC: Investigation, Resources, Supervision, Writing—review and editing. SH: Investigation, Resources, Supervision, Writing—review and editing. XHu: Investigation, Supervision, Writing—review and editing. YH: Investigation, Supervision, Writing—review and editing. YW: Investigation, Resources, Supervision, Writing—review and editing. ZL: Investigation, Resources, Supervision, Writing—review and editing. JC: Investigation, Resources, Writing—review and editing. PG: Supervision, Writing—review and editing. QC: Investigation, Supervision, Writing—review and editing. SJ: Investigation, Supervision, Writing—review and editing. JM: Investigation, Supervision, Writing—review and editing. XZ:

Investigation, Supervision, Writing–review and editing. XT: Investigation, Supervision, Writing–review and editing. YL: Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2024.1429718/full#supplementary-material>

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