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Research article

Risk effects of meteorological factors on human brucellosis in Jilin province, China, 2005–2019

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A R T I C L E I N F O

Keywords:
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A B S T R A C T

Background: The impact of climate on zoonotic infectious diseases (or can be referred to as climate-sensitive zoonotic diseases) is confirmed. Yet, research on the association between brucellosis and climate is limited. We aim to understand the impact of meteorological factors on the risk of brucellosis, especially in northeastern China.
Methods: Monthly incidence data for brucellosis from 2005 to 2019 in Jilin province was obtained from the China Information System for Disease Control and Prevention (CDC). Monthly meteorological data (average temperature (°C), wind velocity (m/s), relative humidity (%), sunshine hours (h), air pressure (hPa), and rainfall (mm)) in Jilin province, China, from 2005 to 2019 were collected from the China Meteorological Information Center (http://data.cma.cn/). The Spearman's correlation was used to choose among the several meteorological variables. A distributed lag non-linear model (DLNM) was used to estimate the lag and non-linearity effect of meteorological factors on the risk of brucellosis.
Results: A total of 24,921 cases of human brucellosis were reported in Jilin province from 2005 to 2019, with the peak epidemic period from April to June. Low temperature and low sunshine hours were protective factors for the brucellosis, where the minimum RR values were 0.50 (95 % CI = 0.31–0.82) for −13.7 °C with 1 month lag and 0.61 (95 % CI = 0.41–0.91) for 110.5h with 2 months lag, respectively. High temperature, high sunshine hours, and low wind velocity were risk factors for brucellosis. The maximum RR values were 2.91 (95 % CI = 1.43–5.92, lag = 1, 25.7 °C), 1.85 (95 % CI = 1.23–2.80, lag = 2, 332.6h), and 1.68 (95 % CI = 1.25–2.26, lag = 2, 1.4 m/s). The trends in the impact of extreme temperature and extreme sunshine hours on the transmission of brucellosis were generally consistent.
Conclusion: High temperature, high sunshine hours, and low wind velocity are more conducive to the transmission of brucellosis with an obvious lag effect. The results will deepen the understanding of the relationship between climate and brucellosis and provide a reference for formulating relevant public health policies.

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1. Introduction

Brucellosis, also known as Mediterranean flaccid fever or wave fever, is a zoonotic infectious disease caused by Brucella. According to statistics, more than 170 countries or regions worldwide have brucellosis outbreaks, with nearly 500,000 new cases worldwide each year, affecting local economic development and seriously threatening people's lives and health [1,2]. And in the context of the COVID-19 epidemic global pandemic, brucellosis in China has a significant positive increase in 2020 and 2021 [3]. Brucellosis poses a growing burden on human health. To date, no vaccine is still available for human brucellosis, and vaccines for animal brucellosis also have many shortcomings [4]. Therefore, the rate of initial treatment failure and recurrence of brucellosis are both very high [5].

Many factors influence the prevalence of brucellosis, such as high-risk occupations, consumption of raw dairy products, and knowledge of relevant prevention [6,7], which leads to a wide range of susceptible people of all ages and genders, especially shepherds, slaughterhouse workers, and veterinarians, who are more vulnerable to the disease. Moreover, related studies have shown that climate suitability for infectious diseases increases with changes in meteorological factors [8]. How climate change, environmental and ecosystem disturbances, vector insect exposure, and the spread of contagious diseases interact and influence each other has been well documented [9,10]. This implies a relationship between climate and brucellosis [1,11,12]. Since the mid to late 1990s, brucellosis incidence has sharply risen, contrasting with the 1990 report of the Intergovernmental Panel on Climate Change (IPCC) highlighting significant temperature rise during the second half of the 20th century [13,14]. Liu et al. found that temperature, sunshine hours, and evaporation affected seasonal fluctuations in brucellosis and that the strongest cumulative effect on the incidence of brucellosis was found at 17.4 °C [15]. Cao et al. noted that air pressure, wind speed, average temperature, and relative humidity significantly affected brucellosis [16]. Another study found that human brucellosis cases in mainland China peaked from March to August and noted the importance of studying the drivers behind seasonality [17]. In this regard, many scholars have suggested that climatic factors may indirectly affect the ecology of brucellosis by influencing livestock reproduction, pathogen replication, and herd immunity [11,18,19]. However, fewer studies have examined the impact of climatic factors on this significant zoonotic disease, and the transmission mechanisms are unclear [20]. Therefore, it is necessary to understand the quantitative relationship between climatic factors and the incidence of brucellosis, especially in today's rapid socio-economic development, leading to increasingly serious problems of environmental pollution and climate change, and exploring the epidemiological patterns between environmental exposure factors and infectious diseases will have a crucial impact on population health.

In this study, we selected Jilin province, a northern region of China, as the study area and collected 15 years of data from the region to estimate the lag and non-linearity of meteorological factors on the risk of brucellosis by building a distributed lag non-linear model (DLNM).

2. Materials and methods

2.1. Study area

In China, brucellosis is mainly prevalent in the northern regions [17]. Jilin province, with a spatial extent of 40°50′-46°19′N and 121°38′-131°19′E, is located in the central part of northeast China. It is adjacent to Inner Mongolia, Heilongjiang, and Liaoning provinces, which have severe brucellosis outbreaks in China (Supplementary Fig. 1). Animal husbandry in Jilin region is well-developed. Frequent activities such as raising and trading livestock, mainly sheep and cattle, make it suitable for spreading brucellosis. Therefore, it is one of the areas in China where brucellosis is prevalent [21]. Jilin province has a temperate monsoon climate, with an average temperature below −11 °C in winter and an average above 23 °C in summer. The annual temperature difference is 35–42 °C, the daily difference is generally 10–14 °C, its annual average sunshine duration is 2259–3016 h, and the average yearly precipitation is 400–600 mm (www.jl.gov.cn/). No studies have investigated the influence of climatic factors on brucellosis in Jilin province.

2.2. Data collection

Monthly brucellosis incidence data from 2005 to 2019 in Jilin province is obtained from the China Information System for Disease Control and Prevention (CDC). In China, human brucellosis is classified as a notifiable category B infectious disease. Cases of human brucellosis, defined by the Diagnosis of Brucellosis (2023 edition), must be reported to the local CDC [22]. The brucellosis epidemic monitoring system operates as a passive monitoring mechanism. Medical and health institutions at all levels nationwide are required to report brucellosis cases through the infectious disease network reporting system within 24 h after diagnosis. This system primarily monitors the incidence and mortality rates of brucellosis in the population. Monthly meteorological data for the same period is from the China Meteorological Information Center (http://data.cma.cn/), including average temperature (°C), wind velocity (m/s), relative humidity (%), sunshine hours (h), air pressure (hPa) and rainfall (mm). This platform is dedicated to promoting the optimal allocation of scientific and technological resources and achieving open sharing. Applicants obtain the corresponding meteorological data by registering as users on this platform. Our research group registered as a user through institution and obtained meteorological data.

2.3. Statistical analysis

A time series database of the collected data is created. We performed a descriptive analysis of the cases of brucellosis and meteorological factors to explore the seasonality of brucellosis incidence and the potential association with meteorological factors. Meteorological factors could be highly correlated among each other and therefore to avoid multicollinearity, we used Spearman's correlation to choose among the several meteorological variables. The formula for Spearman's rank correlation coefficient is as follows:

$$r_s = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)}$$

Where r_s represents the Spearman's rank correlation coefficient, n represents the sample size, and d_i represents the difference in ranks between the two sets of data. The coefficient spans from −1 to 1, with −1 signifying a complete negative correlation, 0 indicating no correlation, and 1 representing a perfect positive correlation. In this study, the exclusion criterion of multicollinearity is $|r_s| > 0.7$ [23,24].

DLNM is based on the definition of cross-basis, a bi-dimensional function expressed by the combination of two basis functions, which depicts the effects of predictor and lags simultaneously [25,26]. This study established a DLNM model to explore the effect of meteorological factors on the incidence of brucellosis. The primary model was as follows:

$$Log[E(Y_t)] = \alpha + cb(X_{t,1}, lag) + ns(time, df) + \sum ns(Z_{t,1}, df) + month$$

Where t is the month of the observation, Y_t is the observed monthly case counts in Jilin during month t, $E(Y_t)$ is the expected number of influenza case counts during month t, α is the intercept; $cb()$ represents the two-dimensional model used to fit the non-linearity and lag months of meteorological parameters by using cross-basis function. $X_{t,1}$ means the meteorological parameters and $Z_{t,1}$ refers to other meteorological parameters except for $X_{t,1}$. The natural cubic spline (*ns*) function was used to control long-term and seasonality trends. The month is an ordinal variable for the month of the year. We are using the Quasi-Poisson connection to control over-dispersion. We refer to the modeling process of other studies [27] to formulate our modeling strategy to determine the most suitable parameters in the model. We firstly established a preliminary model based on prior knowledge and references from other literature: The cross-basis was modeled by the B-splines (*bs*) function with 3 *df* to describe the nonlinear relationship, the Polynomial (*poly*) functions with 3 to describe the lag effect between meteorological factors and brucellosis, and using the *ns* function with 3 *df* to incorporated other meteorological factors. We then used one-way sensitivity analysis to select essential parameters in the model, with evaluation metrics based on the Quasi-Poisson Akaike information criterion (Q-AIC). Specifically, we adjusted the annual degrees of freedom (*df*) within the range of 1–5, and varied the maximum lag months of meteorological factors (1–7 months) for sensitivity analysis. According to the results, the *df* of a smooth function of time in a regression model was set to 3. Previous studies have used *df* ranging from 2 [28] to 8 [27] *df* per year; The final lag months of meteorological factors in our model was set to 4, and the other two papers on the same topic set the lag to 1 [29] and 6 [15], respectively. The results of the sensitivity analysis are shown in the Supplementary Fig. 2.

We defined $P_{2.5}$ and $P_{97.5}$ for each meteorological factor as extreme climatic weather to study the effect of extreme climatic conditions on the risk of brucellosis. Relative risk (RR) with corresponding 95 % confidence interval was used to estimate these effects. The median of each variable is defined as the baseline reference for calculating the RR value. All statistical analyses were performed using R software (version 4.2.2), mainly with the packages dlnm and splines. All statistical tests were two-sided, and a P-value <0.05 was deemed as statistically significant.

3. Results

3.1. Data analysis

During the study period (2005–2019), 24921 cases of brucellosis were reported in Jilin province. The minimum number of cases per month was 7, the maximum number was 572, and the average was 138.5. The summary statistics of each meteorological factor are shown in Table 1. The medians of speed velocity, average temperature, relative humidity, rainfall, sunshine hours, and air pressure were 2.3 m/s, 7.9 °C, 66 %, 24 mm, 229.6h, and 986.4 hPa, respectively. Fig. 1 shows the time series curves of monthly meteorology and the number of brucellosis cases. The monthly incidence of brucellosis showed a trend of slowly increasing and then decreasing,

Table 1
Summary of the cases of brucellosis and meteorological factors in Jilin, China, 2005–2019.

Variables	Mean	SD	Min	Quartiles			Max
				P_{25}	P_{50}	P_{75}	
Cases of brucellosis	138.5	100.4	7	72	108	181	572
Wind velocity(m/s)	2.4	0.5	1.4	2	2.3	2.7	3.9
Temperature(°C)	5.9	13.7	−19.5	−5.6	7.9	18.0	25.7
Relative humidity(%)	70	10	36	57	66	72	86
Rainfall(mm)	56.3	70.6	0	10.6	24.0	77.5	484.5
Sunshine hours(h)	228.4	40.0	110.5	202.3	229.6	257.9	332.6
Air pressure(hPa)	985.7	6.9	972.8	979.5	986.4	991.8	998.5

with most of the epidemic peaks concentrated from April to June. The prevalence curve was single-peaked, with a clear trend and periodicity. Wind speed had two peaks each year: March to April and September to October. Temperature and air pressure had a clear trend, always rising and then falling. Supplementary Table 1 shows the lag correlation between the cases of brucellosis and each meteorological factor. At a lag of 4 months, temperature, rainfall, and air pressure had the greatest correlation with brucellosis, being −0.63, −0.54, and 0.61, respectively. The Spearman correlation analysis is shown in Table 2. The results showed a strong correlation between temperature and both rainfall ($r_s = 0.84$, $P < 0.001$) and air pressure ($r_s = 0.90$, $P < 0.001$). A strong correlation between

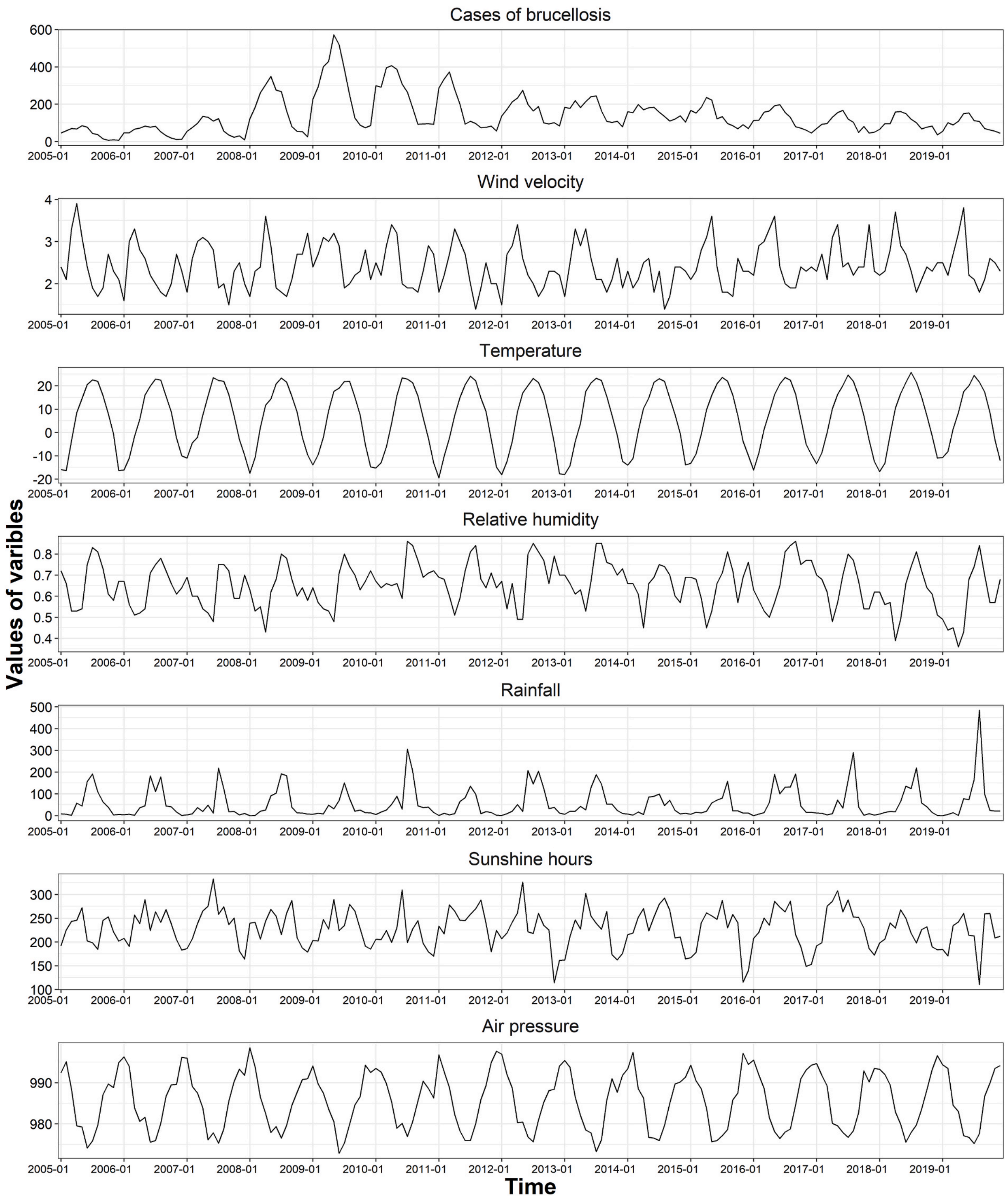

Fig. 1. The time series curves of monthly meteorology and cases of brucellosis in Jilin, China, 2005–2019.

rainfall and air pressure ($r_s = -0.72$, $P < 0.001$) was also found. Therefore, we exclude rainfall and air pressure from the model. Also, there was a strong correlation between relative humidity and wind speed ($r_s = -0.72$, $P < 0.001$), and we excluded relative humidity because it has been shown that wind speed is one of the most effective climatic factors influencing the transmission of brucellosis [16, 30].

3.2. The relationship between meteorological factors and the transmission of human brucellosis

3.2.1. Non-linear and lagged effects of climatic factors on the transmission of human brucellosis

Fig. 2 shows the relationship between climate variables in different lags of months and the risk of brucellosis. Referring to the median monthly temperature (7.9 °C), sunshine duration (229.6h), and wind velocity (2.3 m/s) in Jilin province from 2005 to 2019, each meteorological factor showed a non-linear trend with the risk of brucellosis in the different lag month. Fig. 3 shows a curve plot of meteorological factors and risk of brucellosis at lag 1–4 months. The result showed that low temperature had a protective effect, while high temperature was a risk factor affecting brucellosis. Moreover, whether it was low or high temperature, the impact on the incidence of brucellosis was more significant in a shorter lag period. The protective or risk effects gradually decreased with the extension of the lag time. When the lag time was 1 month, and the temperature was −13.7 °C, the RR value was the minimum (RR = 0.50, 95 % CI = 0.31–0.82). In terms of sunshine hours, low sunshine hours showed a robust protective effect, and its effect gradually decreased with increasing sunlight. High sunshine hours was a risk factor for the brucellosis, and its impact gradually decreased with decreasing sunlight. The RR value was maximum when the lag time was two months when the sunshine hours were 332.6 (RR = 1.85, 95 % CI = 1.23–2.80). Both low sunlight hours and high sunshine hours had a lasting effect on the transmission of brucellosis. As for wind velocity, low wind velocity showed a more substantial risk effect, and high wind velocity showed a stronger protective effect, and the effect was significant at a lag of more than 2 months. Supplementary Table 2 shows the maximum and minimum RR values for each meteorological factor at 1–4 months lag.

3.2.2. Cumulative effect of meteorological factors on brucellosis

The cumulative effect of each meteorological factor on brucellosis is shown in Supplementary Fig. 3. Before the median reference temperature (7.9 °C), temperature was a protective factor for brucellosis. However, when the temperature was higher than 7.9 °C, the risk of brucellosis gradually increased as the temperature increased. As for sunshine hours, when it was less than or equal to 146h (RR = 0.51, 95 % CI = 0.26–0.99), sunshine hours was a protective factor for brucellosis. When it was greater than or equal to 272h (RR = 1.40, 95 % CI = 1–1.96), it was a risk factor for brucellosis, and with the increase of sunshine hours, the risk of brucellosis increased. When the wind velocity was less than or equal to 1.7 m/s (RR = 2, 95 % CI = 1.12–3.57) and wind velocity was greater than or equal to 2.6 m/s (RR = 1.28, 95 % CI = 1–1.63) and less than or equal to 3.2 m/s (RR = 1.81, 95 % CI = 1–3.10), wind velocity could be regarded as a risk factor for brucellosis, and when it was less than or equal to 1.7 m/s, the smaller the wind velocity, the greater its impact on the incidence of brucellosis. When the wind velocity was between 2.6 m/s-3.2 m/s, it showed an inverted “V” curve relationship with the risk of brucellosis, with a trend of increasing and then decreasing with the increase of wind velocity, and the maximum RR value of wind speed was 3.1 m/s (RR = 1.85, 95 % CI = 1.12–3.05).

3.2.3. Current month lag effect of extreme climate

Fig. 4 shows the current month lag effect of extreme climate (specific RR values and 95 % CI were recorded in the Supplementary Table 3). The results showed that the RR values of extreme low temperature (−17.2 °C) at lag 0–2 months were less than 1, and the results were statistically significant. The RR values of extreme high temperature (23.6 °C) were all greater than 1 at lag 0–2 months, and the results were statistically significant. The $P_{2.5}$ and $P_{97.5}$ of sunshine hours were 151 m/s and 298 m/s, respectively. For extreme low sunshine hours with a lag time of 0.5–2 months, all RR values were less than 1, and the results were statistically significant. For extreme high sunshine hours with a lag time of 0.5–2.5 months, all RR values were greater than 1, and the results were also statistically significant. The RR values of $P_{2.5}$ (1.65 m/s) for wind velocity at lag 0–2.5 months were all greater than 1, and the results were statistically significant, while $P_{97.5}$ (3.6 m/s) for wind speed at lag 0–4 months were not statistically significant. In addition, we plotted the distribution of the lagged effects of $P_{2.5}$, P_{25}, P_{75}, and $P_{97.5}$ of each meteorological factor on the risk of brucellosis, using the median of each meteorological factor as a reference value (Fig. 5). The results showed that the effect of low temperature on the risk of brucellosis was basically the same, and the effect of high temperature on the risk of brucellosis showed a trend of increasing and then decreasing, and the effect of extreme high temperature weather on the risk of brucellosis was more significant. The effect of

Table 2
Spearman’s correlation between meteorological factors.

Variables	Wind velocity	Temperature	Relative humidity	Rainfall	Sunshine hours	Air pressure
Wind velocity	1					
Temperature	−0.17*	1				
Relative humidity	−0.72**	0.34**	1			
Rainfall	−0.19*	0.84**	0.52**	1		
Sunshine hours	0.10	0.58**	−0.19*	0.33**	1	
Air pressure	−0.05	−0.90**	−0.22*	−0.81**	−0.56**	1

*$P < 0.05$; **$P < 0.001$.

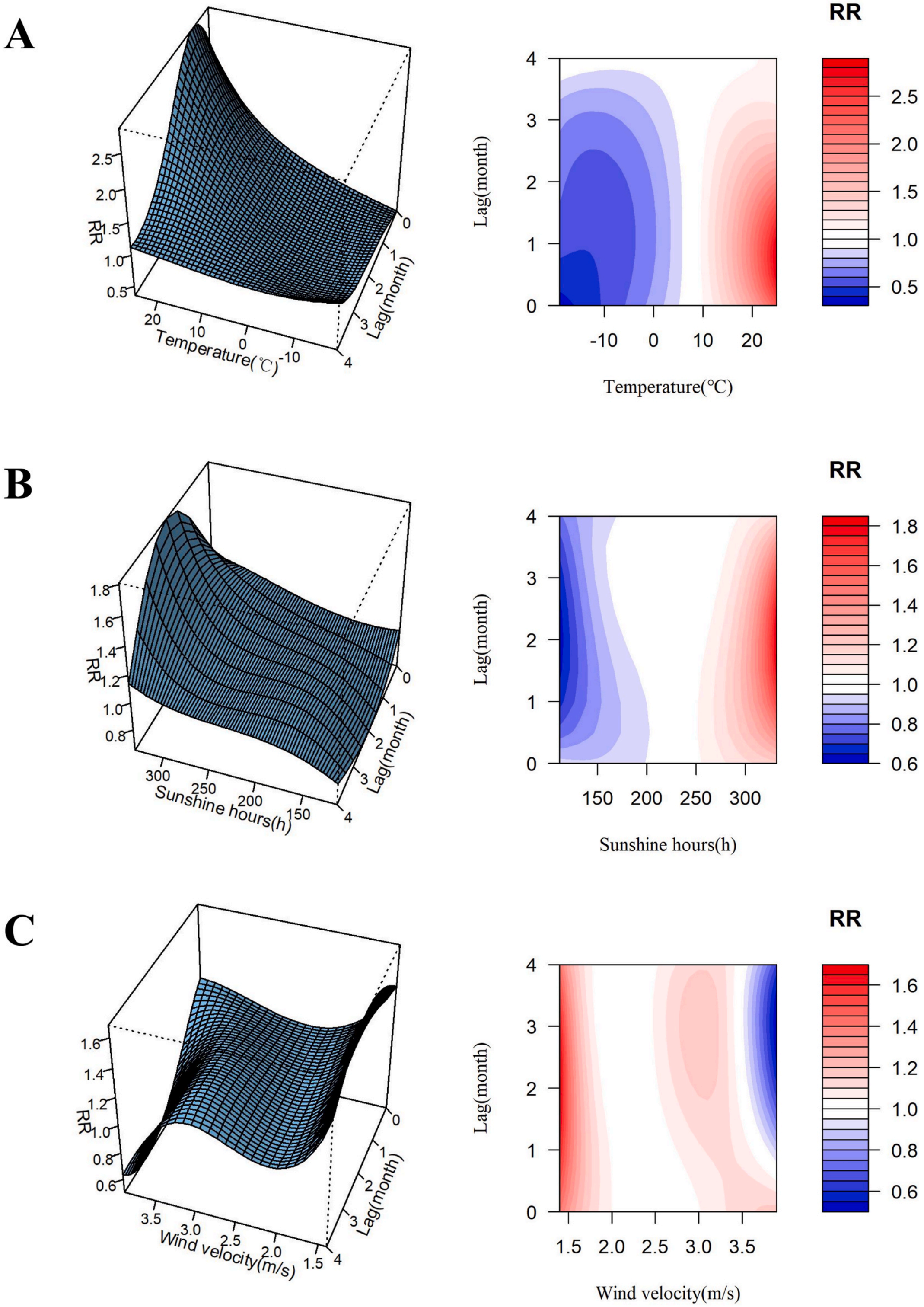

Fig. 2. Three-dimension and Contour graphs of exposure-lag-response for meteorological factors and brucellosis. **(A)** Three-dimension and contour graph of temperature. **(B)** Three-dimension and contour graph of sunshine hours. **(C)** Three-dimension and contour graph of wind velocity.

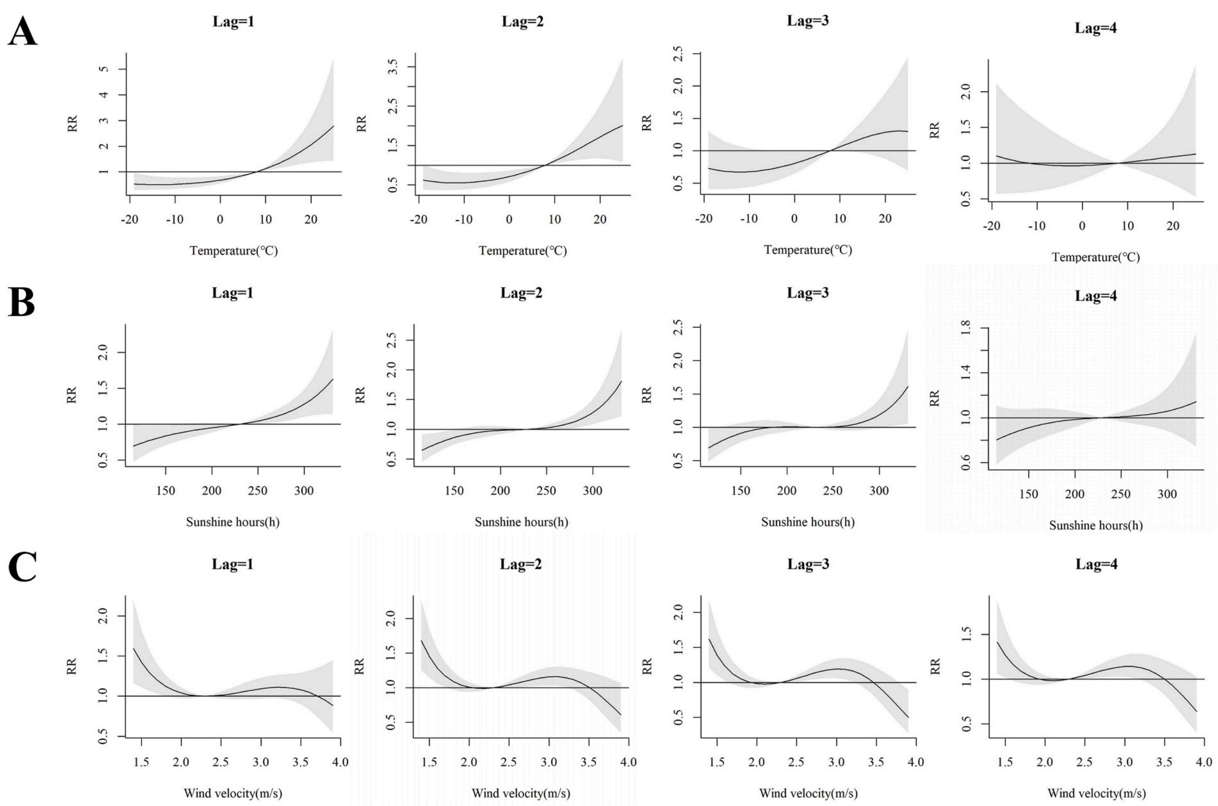

Fig. 3. Curve plots of meteorological factors and risk of brucellosis at lag1-4 months. **(A)** Curve plot of temperature at lag 1–4 months. **(B)** Curve plot of sunshine hours at lag 1–4 months. **(C)** Curve plot of wind velocity at lag 1–4 months.

temperature on the risk of brucellosis diminished with increasing lag time, whether high or low temperature. The trend of the influence of sunshine hours on the risk of brucellosis was basically consistent with temperature.

4. Discussion

This paper investigated the relationship between meteorological factors and brucellosis in Jilin Province from 2005 to 2019 using a DLNM. The model has effectively assessed the relationship between meteorological factors and climate-sensitive infectious diseases, including influenza, hand, foot and mouth disease, dengue fever, chickenpox, etc. [27,31–33]. Using the same model, two previous studies examined the relationship between climatic factors and the risk of brucellosis. One of the studies examined the relationship between climate and brucellosis in northwest China (Yulin city, Shaanxi province) and concluded that temperature, sunshine duration, and evaporation contributed significantly to seasonal fluctuations in brucellosis within 6 months [15]. Another study examined the relationship between brucellosis transmission and climate in northwest China (Yongchang city, Gansu province). It concluded that temperature, sunshine hours, and air pressure increase the risk of brucellosis at different lag times [29]. Our study examined the northeastern region of China, represented by Jilin province. The results showed that the risk of brucellosis had a non-linear relationship with meteorological factors, including temperature, sunshine duration, and wind speed, and there was also a certain lag effect.

Temperature affects the seasonality and intensity of infectious disease transmission [34]. The explanatory power of temperature for the spatially uneven distribution of brucellosis diminishes over time [35]. Our study found that both low and high temperatures had a more significant effect on the spread of brucellosis in a shorter lag time, and the effect diminished as the lag time increased. For example, extreme cold temperatures (−17.2 °C) reduced the risk of brucellosis transmission at a lag of 0 month (RR = 0.38, 95 % CI = 0.19–0.76), while the effect was not statistically significant after a lag of 2.5 months. Brucella is a human-animal bacterium closely associated with animal husbandry. It reproduces faster and exhibits stronger biological activity during warm seasons compared to cold seasons [36]. A Russian study found that increased temperature improves the chances of host survival and increases the risk of zoonotic infections [20]. However, regression analysis by Iranian scholars showed a negative significant correlation between ambient temperature and the risk of brucellosis [37]. And a spatio-temporal study in Inner Mongolia, China, showed that regions with low temperature were more likely to be high-prevalence areas of human brucellosis [38]. Our findings showed that low temperatures reduced the risk of brucellosis transmission, and high temperatures were a risk factor for brucellosis infection. Temperature can affect the survival and transmission of infectious pathogens in the environment, as well as influence human behavior and activities, thereby, to some extent affecting the development of infectious disease transmission [38,39]. We believe that low temperature limit husbandry

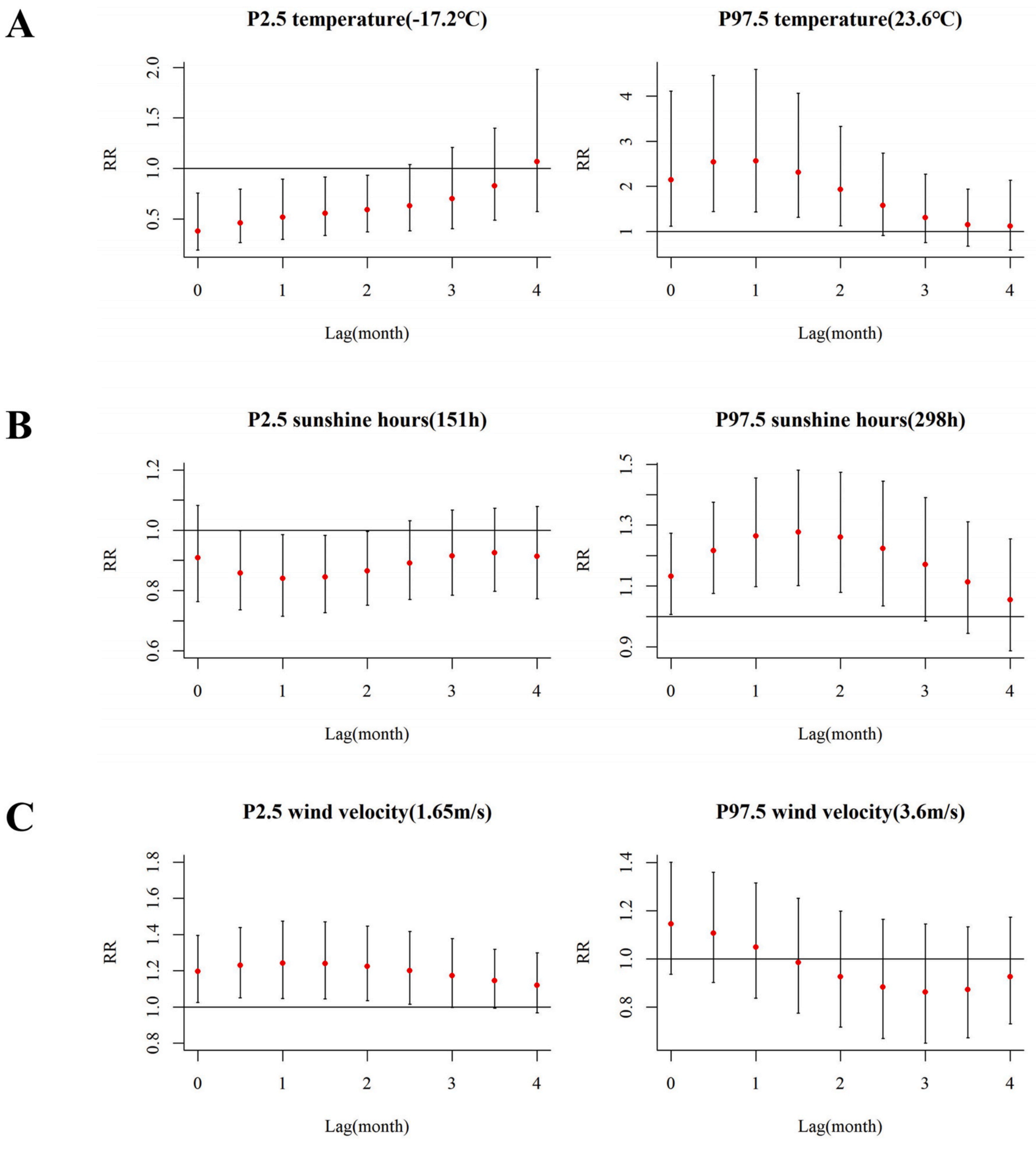

Fig. 4. Separate effects of extreme meteorological (P2.5 and P97.5) on the relative risk of brucellosis with a lag of 1–4 months. **(A)** Extreme temperature on the relative risk of brucellosis with a lag of 1–4 months. **(B)** Extreme sunshine hours on the relative risk of brucellosis with a lag of 1–4 months. **(C)** Extreme wind velocity on the relative risk of brucellosis with a lag of 1–4 months.

activities, including shearing, breeding, and free trade of livestock products such as dairy and meat, thereby reducing the risk of exposure to susceptible individuals. Most animals infected with brucellosis show no obvious signs and infect susceptible people mainly through abortion and secretions [40]. Suitable high temperature environment is conducive to the propagation and growth of brucella [18], and the warm season is conducive to the estrus of sheep and goats, which not only increases the density of sheep but also facilitates the spread of brucellosis among animals. It also increased livestock production and increased contact between humans and infected animals.

Our study found that extreme low wind velocity (1.65 m/s) at a lag of 0–2.5 months increased the risk of brucellosis transmission. A study investigated the effect of meteorological factors on brucellosis by developing a Markov switching model (MSM) and found that low wind speed (1.89 m/s) at a lag of 1 month predicted the highest incidence of brucellosis [41]. Both had similar findings. High wind velocity can reduce disease because bacteria have a shorter life span in the air [42]. The increase in evaporation significantly drives the incidence of brucellosis, while the increase in wind speed amplifies evaporation. Therefore, wind speed indirectly influences the spread

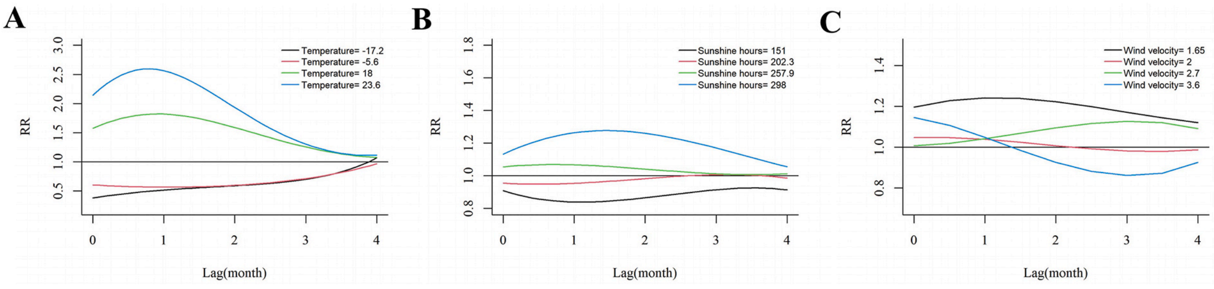

Fig. 5. Effect of quantile values (P2.5, P25, P75, P97.5) of meteorological factors on the relative risk of brucellosis. **(A)** The quantile values of temperature on the relative risk of brucellosis. **(B)** The quantile values of sunshine hours on the relative risk of brucellosis. **(C)** The quantile values of wind velocity on the relative risk of brucellosis.

of brucellosis through its impact on evaporation [16,43]. However, high wind velocity can drive Brucella hidden in animals and feces to the eyes and respiratory tracts of susceptible people. It can also cause skin cracking, increasing the chance of pathogen invasion [44]. However, our results showed that high wind velocity was not statistically significant in increasing the risk of brucellosis transmission. At the same time, our finding that low wind speed correlates with an increase in brucellosis incidence may seem counterintuitive, especially considering that Brucella is considered a potential bioterrorism agent. We believe that low wind speed may lead to air stagnation, particularly in enclosed or semi-enclosed environments. In such circumstances, low wind speed may facilitate the retention and transmission of Brucella bacteria within the local environment. Additionally, individuals may be more inclined to go outdoors during periods of low wind speed, thereby increasing their exposure to Brucella [44].

Regarding the impact of sunshine hours on the spread of brucellosis, some studies have found that extreme weather with high sunshine hours reduces the transmission of brucellosis [18,36]. However, our results showed that high sunshine hours increased the risk of brucellosis and had a significant lag effect. The maximum relative risk was 1.85 (1.23–2.80) when the sunshine hours was 332.6h with two months lag. Our view can be supported by the fact that extreme weather with high sunshine often occurs in spring and summer, which are the most common periods of brucellosis. In addition, high levels of sunlight and evaporation can cause drought and limit plant germination [15]. As a result, cattle and sheep have reduced feed intake and weight gain in spring and summer. They are more susceptible to gastrointestinal parasites due to high temperature and humidity conditions, leading to reduced immunity and increased risk of brucellosis infection [45].

It is worth noting that this study is based on an ecological design, focusing on population-level observations, which means that the

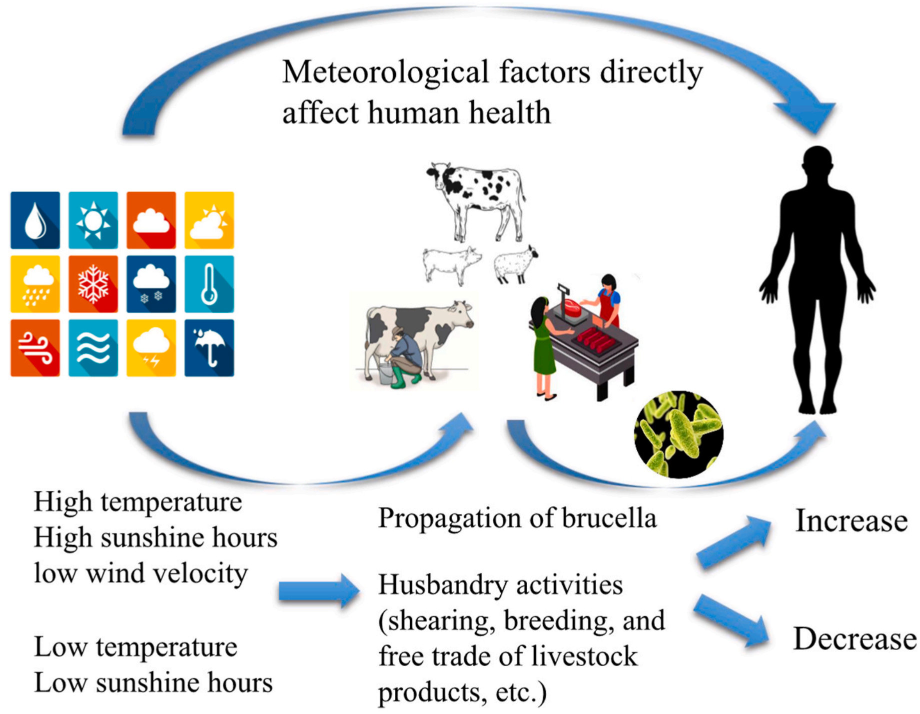

Fig. 6. Mechanisms of meteorological factors and brucellosis.

results cannot be extrapolated to individuals. Thus, ecological fallacy is inevitable. Additionally, the impact of meteorological factors on the transmission of brucellosis does not imply direct causality. In this process, human activities and behaviors adjusted by meteorological factors play a crucial role in the transmission of brucellosis. Fig. 6 effectively illustrates this point. Fig. 6 depicts the mechanism among meteorological factors, human behaviors, and the transmission of brucellosis. Firstly, meteorological factors directly affect human physiology, increasing or decreasing the likelihood of Brucella invasion. Human activities themselves affect the transmission of brucellosis, which is manifested as a direct influence. Furthermore, meteorological factors indirectly affect the transmission of brucellosis by influencing human behavioral activities, such as milking, shearing, and feeding of cattle and sheep, as well as the trade of livestock products. Last but not least, distinguishing between climate change and seasonal variation is crucial for understanding the study results. Seasonal patterns allow us to establish baseline data and observe trends over time. By analyzing these long-term trends, we can indirectly infer the potential effects of climate change on meteorological variables and ecological processes. While our study may not directly measure climate change, it provides valuable insights into how ecosystems may respond to long-term shifts in weather patterns, thereby affecting human behavior and the transmission of zoonotic diseases.

Our study contributes to understanding the impact of meteorological factors on the risk of brucellosis, especially in northeastern China. For example, brucellosis activity will intensify in the next three months when the environment is hot or has low wind velocity or high sunshine hours. This may inform local health departments in developing effective prevention strategies. However, our study has certain limitations. Although monitoring data can better reflect the nonlinear relationship between meteorological factors and infectious diseases [46,47], improving the accuracy of time series models requires research based on large amounts of data [48]. In addition, extreme weather conditions such as haze and dust storms have a great impact on the spread of infectious diseases, and it may be possible to add meteorological parameters related to air pollution to the model to more comprehensively and accurately investigate the impact of meteorological factors on the spread of brucellosis. Furthermore, due to the absence of individual patient data, we could not analyze other risk factors among patients, such as occupation, close contact with animals, and consumption of dairy products, despite their potential impact on brucellosis.

5. Conclusion

This study provided evidence for the close relationship between brucellosis transmission and climatic factors in Jilin Province. The results showed that low temperature and low sunshine duration were protective factors for brucellosis in Jilin province, while high temperature, high sunshine duration, and low wind speed were more conducive to Brucella activity, and the lag effect was obvious within four months. The results of this study help provide a reference for local public health personnel to formulate preventive and control measures.

Data availability statement

Data will be made available on request.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

All the authors consent when it is published.

CRediT authorship contribution statement

Shanjun Huang: Writing – original draft, Software, Methodology, Formal analysis. **Hao Wang:** Supervision, Software, Resources. **Zhuo Li:** Software, Resources, Methodology. **Zhaohan Wang:** Software, Resources, Methodology. **Tian Ma:** Software, Resources, Formal analysis. **Ruifang Song:** Resources, Methodology. **Menghan Lu:** Supervision. **Xin Han:** Supervision. **Yiting Zhang:** Supervision. **Yingtong Wang:** Supervision. **Qing Zhen:** Supervision, Project administration, Conceptualization. **Tiejun Shui:** Supervision, Data curation.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e29611.

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