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Can Climate Change Increase the Spread of Animal Diseases? Evidence from 278 Villages in China

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Abstract: Several countries are currently evaluating the potential health impacts of climate change (CC), particularly in relation to the complex connections between CC-induced weather fluctuations. China, heavily affected by CC, provides clear evidence of its effects. Previous research in animal sciences indicates that factors like temperature, humidity, precipitation, and wind speed can affect animal epidemics. In China, a major global hub for animal husbandry, these factors pose significant challenges, warranting further investigation into their quantitative relationship with disease outbreaks. This study investigates the influence of these climatic conditions on epizootic diseases in China. In the current study, using data from 278 village-level surveys and daily meteorological data spanning 2012 to 2018, we used a fixed-effect model for analysis. The findings reveal that increasing temperatures and wind speeds exacerbate disease development, while the precipitation anomaly index negatively impacts animal epidemics, with humidity showing minimal influence. Addressing CC's potential impact on animal disease, governments, organizations, and farmers need to pay more attention to the impacts of climate change on animal diseases and work together to better cope with the impacts through policies, measures, and research.

Keywords: climate change; air quality; health; animal diseases; climate factors; sustainable

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1. Introduction

Global climate change (CC) is an established fact, evident through temperature rise, ocean warming, and sea-level elevation, yielding complex and far-reaching impacts. During 2011–2020, the global surface temperature exceeded that of 1850–1900 by 1.09 [0.95 to 1.20] °C. The probability of global warming exceeding 1.5 °C in the near future (2021–2040) stands at a minimum of 50%, even in scenarios of very low greenhouse gas emissions [1]. CC is anticipated to escalate the frequency and severity of extreme events [2]. The Sixth Assessment Report by the IPCC underscores the increasing global influence of CC on ecosystems (terrestrial, freshwater, and oceanic) and human systems (water security, food production, health and well-being, urban areas, settlements, infrastructure, etc.). These effects are not uniform across regions. China, as one of the most sensitive and significant regions, exemplifies the impact of global CC. From 1951 to 2021, China witnessed an annual mean surface temperature rise rate of 0.26 °C/10 years, significantly surpassing the global average of 0.15 °C/10 years for the same period. Additionally, between 1961 and 2021, China experienced a rising trend in average annual precipitation and extreme heavy precipitation events. Since the late 1990s, extreme high-temperature events have shown a notable increase, while extremely low-temperature events have exhibited a significant decrease [3].

Presently, animal diseases pose a significant threat to the global economy and public health. Existing studies reveal that the adverse impact of animal epidemics extends beyond animals and animal husbandry itself, permeating a broader spectrum encompassing production, daily life, and trade systems. This influence ripples downstream in the industrial chain through the food system, affecting human well-being and health through human–animal interactions, and impacting consumer welfare via trade and consumption [4–6]. Furthermore, nearly one-fifth of the global population engages in the production, processing, and marketing of animals and their products. For these individuals, animal diseases transcend being solely a health concern, as they also jeopardize their livelihoods [7]. China, as the world's largest livestock producer, grapples with the persistent threat of animal diseases. According to statistics from the Veterinary Bulletin of the Ministry of Agriculture and Rural Affairs, animal diseases have perennially perplexed animal husbandry in China. From 2013 to 2014, the H7N9 flu epidemic wreaked havoc on China's poultry industry, resulting in direct economic losses exceeding 100 billion RMB. During the same period, the outbreak of PPR imposed restrictions on the live sheep trade, significantly driving down live sheep prices and inflicting substantial losses upon Chinese farmers. Notably, the outbreak of African swine fever in 2018 precipitated a 25% decline in China's pork production in 2020 compared to 2017 [8].

Numerous discussions have revolved around the effect of climate factors such as temperature and rainfall sensitivity on flora and fauna [9–12]. There have also been studies that have looked at the impact of global CC on the occurrence and spread of animal diseases [13–16]. Survey responses from OIE members have unveiled significant concerns among animal health officials, with 71% expressing apprehension about CC's influence on emerging and re-emerging animal diseases. Additionally, 58% of members have identified several vector-borne diseases linked to CC [17]. Ahmed [18] emphasized the role of CC in causing at least one emerging or re-emerging disease in numerous countries, with a growing number of nations experiencing such incidents. Howden et al. [19] drew attention to the potential adverse effects of CC on sheep health in Australia, foreseeing an increase in the incidence of pests and diseases. CC has wide-ranging effects, altering disease and pest distributions, prevalence, incidence, and seasonality [20,21]. Diseases that were once confined to specific regions are now expanding their reach and affecting previously unsusceptible species [22,23].

Furthermore, CC disrupts bird migration, influences the transmission cycle of avian influenza viruses (AI viruses), and directly impacts virus survival outside their hosts [24]. Rising elevations may lead to increased avian malaria transmission year-round [25]. However, the extent of CC's influence remains highly uncertain [21], and there exists a substantial knowledge gap regarding the causal chain linking CC and disease outbreaks [26,27]. For contagious animal diseases, climate may be more closely associated with the seasonal occurrence of diseases rather than their spatial propagation [28]. Notably, CC does not uniformly elevate the risk of all diseases; many livestock diseases will be minimally affected or remain unaffected, particularly those primarily transmitted through close host contact or foodborne routes [29]. Specific impact assessments remain limited. Marcos-López [30] introduced a risk framework to scrutinize CC's influence on disease emergence in the United Kingdom. Additionally, a study calculated the correlation coefficient between animal diseases and meteorological factors by utilizing data from all animals in Beijing Zoo and daily meteorological data from Beijing between 1975 and 1998 [31].

The trend of CC is unmistakably clear. Will it increase the incidence of animal diseases? Few studies confirm or disprove the impact of CC on animal disease occurrence, making it difficult to address this impact effectively through prevention and interventions in animal production. Unlike human health, many countries lack adequate animal disease surveillance and reporting. The absence of disease surveillance and reporting data constitutes one of the key reasons for the sluggish progress of empirical research. Drawing on panel data from 278 villages in China spanning the years 2012 to 2018, this study endeavors to estimate the specific impact of climatic factors on animal diseases in China. It aims to comprehend which climatic factors influence the occurrence of animal diseases, as well as the manner and extent of their influence. The primary contribution of this study lies in enhancing our understanding of the quantitative relationship between climatic factors and animal disease outbreaks, providing valuable support for more effectively addressing the challenges posed by CC.

This article is divided into six parts. Following the introduction, a review of the literature is presented in Section 2. The materials and methods are presented in Section 3. Section 4 describes the results, Section 5 is the discussion part, and finally, Section 6 outlines the conclusions of the study.

2. Literature Review

2.1. Climate Change and Animal Disease

CC is an ongoing phenomenon that has been identified as a threat to various ecosystems around the world. It has a direct impact on the health and well-being of humans and animals. One of the significant impacts of CC is the potential exacerbation of animal diseases. The emergence of new infectious diseases or the re-emergence of previously controlled diseases can be linked to changes in the environment, including temperature, precipitation, and extreme weather events [32,33]. This literature review considers the relationship between CC and animal diseases and discusses the possible mechanisms through which CC can exacerbate outbreaks of animal diseases. CC can have a direct or indirect impact on animal health. Direct impacts include heat stress, dehydration, and changes in habitat availability [34,35]. Indirect impacts include changes in the distribution and abundance of vectors and hosts, alteration of the host–pathogen relationship, and changes in the duration and intensity of infectious diseases. These impacts can increase the likelihood of the emergence or re-emergence of infectious diseases in animals. A study conducted by Altizer et al. [35] found that CC is a significant driver of emerging infectious diseases in animals. The study found that temperature increases, extreme weather events, and changes in precipitation patterns have contributed to the emergence of several infectious diseases, including avian influenza, West Nile virus, and Lyme disease. Similarly, a study by Altizer et al. [35] found that CC has been linked to the re-emergence of several infectious diseases in wild animals in the Arctic and sub-Arctic regions. The study found that the warming of these regions has led to changes in the distribution and abundance of wildlife hosts and vectors, resulting in the emergence of infectious diseases, such as brucellosis and tularemia. Furthermore, a study by Swaminathan et al. [36] highlighted the potential for CC to exacerbate the spread of infectious diseases in domestic animals.

The study found that CC can lead to changes in the distribution and abundance of vectors and hosts, which can increase the risk of transmission of several infectious diseases, including bluetongue virus and Rift Valley fever. The impact of CC on animal diseases can be attributed to several mechanisms. One of the primary mechanisms is the alteration of the host–pathogen relationship. Changes in temperature, precipitation, and humidity can affect the host's immune system and the pathogen's replication rate, leading to an increase in the likelihood of disease transmission [36]. Another mechanism is the change in the distribution and abundance of vectors and hosts. Changes in temperature and precipitation can alter the habitat and behavior of vectors and hosts, leading to changes in the geographical range and seasonality of infectious diseases [36]. For example, the expansion of the geographical range of the Asian tiger mosquito has been linked to CC, which has led to the transmission of several infectious diseases, including dengue fever and chikungunya [37]. In conclusion, CC is a significant driver of emerging and re-emerging infectious diseases in animals. The impact of CC on animal diseases can be attributed to several mechanisms, including alterations in the host–pathogen relationship and changes in the distribution and abundance of vectors and hosts. Understanding the relationship between CC and animal diseases is crucial for developing effective strategies for the prevention and control of these diseases.

2.2. Climate Change and Transmission Ecology of Animal Disease

CC has been identified as a significant factor in the transmission ecology of animal diseases. The changing climate is affecting the distribution and abundance of vector-borne diseases, such as mosquito-borne diseases, tick-borne diseases, and water-borne diseases, which are responsible for significant public health concerns worldwide [32,38,39]. The increase in global temperature has resulted in changes in the habitat and behavior of vectors, leading to the expansion of their range and an increased risk of disease transmission. For instance, the increased occurrence of warm weather due to CC has resulted in the expansion of the geographical range of diseases such as Lyme disease and West Nile virus in North America. Furthermore, CC can also impact the host–pathogen relationship by altering the physiology and behavior of animals, thereby affecting the prevalence of diseases. For example, CC has been linked to the spread of a fungal disease, white-nose syndrome, that has decimated bat populations in North America [40]. To mitigate the impacts of CC on the transmission ecology of animal diseases, it is important to implement effective disease surveillance and control measures, as well as to address the underlying environmental and social factors that contribute to disease transmission [41,42]. Additionally, there is a need for greater research and collaboration among public health professionals, ecologists, and climatologists to develop effective strategies for preventing and controlling the spread of animal diseases in the face of CC.

3. Material and Methods

3.1. Framework of the Study

Based on the existing literature, we provide a summary of the mechanisms through which CC impacts animal diseases. This summary establishes a logical framework and theoretical foundation for our quantitative analysis (Figure 1). CC can influence animal diseases both directly and indirectly [21,29]. It leads to alterations in mean climatic conditions and variability, encompassing temperature, precipitation, humidity, and wind, as well as modifications in extreme weather events, including changes in their frequency, severity, and geographic distribution. These shifts in climate variables and extreme climate events can directly impact pathogens, vectors, hosts, and their interrelationships, thereby influencing the occurrence of animal diseases, such as the emergence of new diseases and the re-emergence of existing ones. Furthermore, CC affects the spread and distribution of animal diseases, including their spread patterns, seasonality, spatial range, and affected species. For instance, warmer and wetter conditions can elevate the incidence of heat-related and infectious diseases [43].

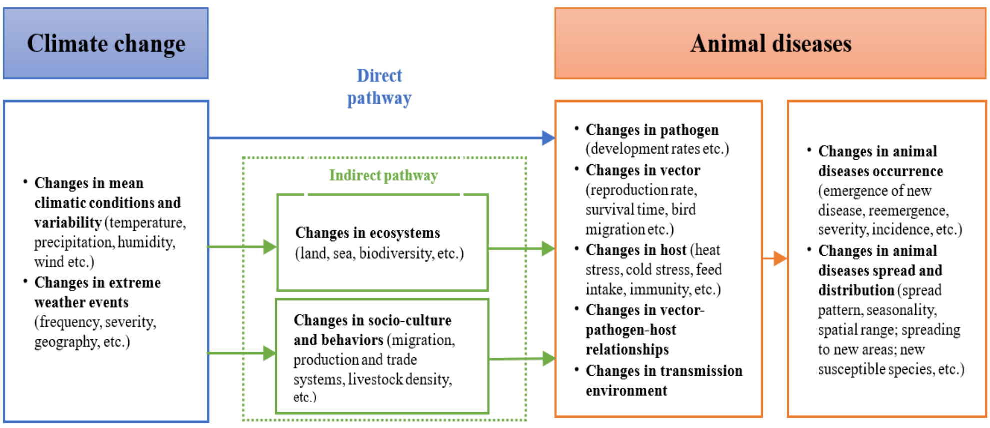

Figure 1. Illustration of the direct and indirect pathways through which CC influences animal diseases [19,21,23–25,29,43,44].

CC also brings about changes in ecosystems (land, sea, biodiversity), and adaptive changes in socio-culture and behaviors (migration, production, trade systems, livestock density), which also influence climate factors and the occurrence of animal diseases. This process can be defined as the indirect pathway of CC affecting animal diseases. For example, CC may affect future patterns of livestock density, distribution, and production, and trade could affect the probability of an infected or infested animal contacting a susceptible one and thus affect the risk of disease spread [29] (Figure 1).

3.2. Model Specifications

This study primarily focuses on empirically analyzing the effects of climate variables, including temperature, precipitation, humidity, and wind speed, on the occurrence of animal diseases. We utilize village panel data from China spanning the years 2012 to 2018. Given the significant variations in physical geography and socio-economic conditions across different regions in China, each village possesses unique characteristics that may impact the occurrence of animal diseases. Additionally, there is a yearly fluctuation in the overall prevalence of animal diseases, which can also influence their occurrence. Hence, we adopt a two-way fixed effects model. To ascertain the presence of individual fixed effects and timefixed effects, we employ the Hausmann test and the joint significance test of annual dummy variables. More precisely, the estimating equation in the current study takes the following form:

$$D_{it} = \beta_0 + \beta_1 C_{it} + V_i + V_t + \varepsilon_{it}$$

where D_{it} is the variable related to animal disease occurrence in a village i and year t; C_{it} is the variable related to climate; V_i is the village fixed effect; V_t is the time fixed effect; i and t represent the village and year separately; β_0, β_1 are coefficients; and ε_{it} is the standard error.

The dependent variable was the animal disease-related variable, which was measured by whether the village had an animal major epidemic event identified by the higher government in that year (According to the Animal Epidemic Prevention Law of the People's Republic of China, animal epidemics shall be identified by the competent agricultural and rural departments of the people's governments at or above the county level. Major animal epidemics shall be identified by the competent department of agriculture and rural affairs of the people's governments of provinces, autonomous regions, and municipalities directly under the Central Government, and shall be confirmed by the competent Department of Agriculture and Rural Affairs of The State Council, if necessary. A major animal epidemic refers to a situation in which an animal epidemic of Class I, II, or III occurs suddenly and spreads rapidly, causing a serious threat or harm to the safety of the breeding industry, or possibly causing harm to the health and life of the public). The independent variables were climate-related and mainly considered four aspects: temperature, precipitation, humidity, and wind speed. It has been shown in the literature that extremely hot days may bring heat stress. Therefore, in terms of temperature, not only the average temperature, minimum temperature, and maximum temperature were considered, but also the influence of high-temperature days was considered. To identify sensitive temperatures, the effects of different temperatures ranging from 35 °C to 45 °C were measured, and they are determined according to the significance level of the estimation. In addition to the average precipitation, the influence of extreme precipitation is also considered in the analysis of precipitation influence, which is mainly measured by the precipitation anomaly index. The influence analysis of humidity and wind speed mainly considered the influence of average humidity and wind speed. Specific variables are set in Table 1.

In terms of regression analysis, on the one hand, according to the existing literature, the impact of climate factors on animal diseases and their mechanism of action is relatively complex, and the lack of quantitative analysis in the existing literature also provides this paper with insufficient data support. Due to the referential nature of variable settings, and the possible high correlation between different climate variables (such as precipitation and humidity), this study attempted to examine whether there is a data regularity between climate variables and animal epidemics in China through univariate analysis. On the other hand, considering that the physical geographical conditions of different regions in China are quite different, and climate variables under different climate conditions may have different effects on animal diseases, in addition to the overall sample analysis, the regression analysis was also carried out on the subsamples of different regions and provinces.

Table 1. Variables setting.

Variable Type		Variable Name	Variable Description
Variables related to animal disease		Occurrence of animal major epidemic diseases	If there was a major epidemic event recognized by the government in the village in the year: 1 = yes, 0 = no
Variables related climate	Temperature	Mean temperature (°C)	The average temperature in the year
		Mean daily minimum temperature (°C)	The mean of daily minimum temperature in the year
		Mean daily maximum temperature (°C)	The mean of daily maximum temperature in the year
		Number of days with high temperature	The number of days with a maximum temperature above a specified temperature in the year
	Precipitation	Mean daily precipitation (mm)	The average daily precipitation in the year
		Precipitation anomaly index	Precipitation anomaly index = (precipitation in this period—average precipitation during the observation period)/average precipitation during the observation period
	Humidity	Mean humidity (%)	The average humidity (Relative humidity: The ratio of the actual water vapor pressure in the air to the saturation water vapor pressure at the current temperature, expressed as a percentage (%)) in the year
	Wind speed	Mean wind speed (m/s)	The average wind speed in the year

3.3. Data Source and Sample Distribution

The data relating to animal diseases used in this research are the microeconomics data of Chinese farms from the Institute of Agricultural Economics and Development of the Chinese Academy of Agricultural Sciences. The data have been collected since 2012. The data selection process involves classifying 31 provincial-level administrative regions into North China, Northeast China, East China, Central South China, Southwest China, and Northwest China, respectively. According to the average value of farmers' per capita net income from 2008 to 2010 in each province, all the provinces in each region were ranked, and the provinces with the average value in the middle were selected. There are eight provinces, including Hebei, Henan, Fujian, Jilin, Shaanxi, Yunnan, Shandong, and Xinjiang. After removing the abnormal samples, the actual data used in this study are 7-year unbalanced panel data with a total sample size of 1436, including 278 administrative villages in the above eight provinces from 2012 to 2018. The sample area covers the major climate types in China and can be divided into three regions: north, south, and northwest. The northern region includes Jilin, Hebei, Henan, Shandong, and Shaanxi, Yunnan and Fujian in the south, and Xinjiang in the northwest. The northern region mainly has a temperate continental climate and a temperate monsoon climate, and four seasons of temperature change are clear. The southern region is dominated by the tropical and subtropical monsoon climate, with high temperatures, rainy summers, and mild and rainy winter. In the northwest region with a temperate continental climate, winters are cold and dry, summers have high temperatures and scarce precipitation, and the diurnal and annual temperature ranges are large. The data related to climate variables used in this research are daily meteorological data of the National Meteorological Administration from 2012 to 2018. We used average temperature, daily minimum temperature, daily maximum temperature, daily precipitation, daily average humidity, and daily average wind speed, originating from weather stations, and the villages are linked to the closest weather station. The above micro survey data of village animal disease occurrence data and meteorological monitoring data provide data conditions for quantitative analysis in this study, which can meet the needs of our research purposes. Sample distribution in both time and location is shown in Table 2 and Figure 2.

Table 2. Sample distribution in both time and location.

Provinces Name	Hebei	Jilin	Fujian	Shandong	Henan	Yunnan	Shaanxi	Xinjiang	Total
Number of villages	27	27	40	25	27	27	47	58	278
2012	27	27	27	25	27	27	18	42	220
2013	27	26	26	23	26	26	14	43	211
2014	27	24	24	16	26	27	23	50	217
2015	26	24	24	19	21	25	24	42	205
2016	25	27	26	22	19	25	17	37	198
2017	25	24	26	22	16	25	22	38	198
2018	26	25	18	24	21	26	18	29	187

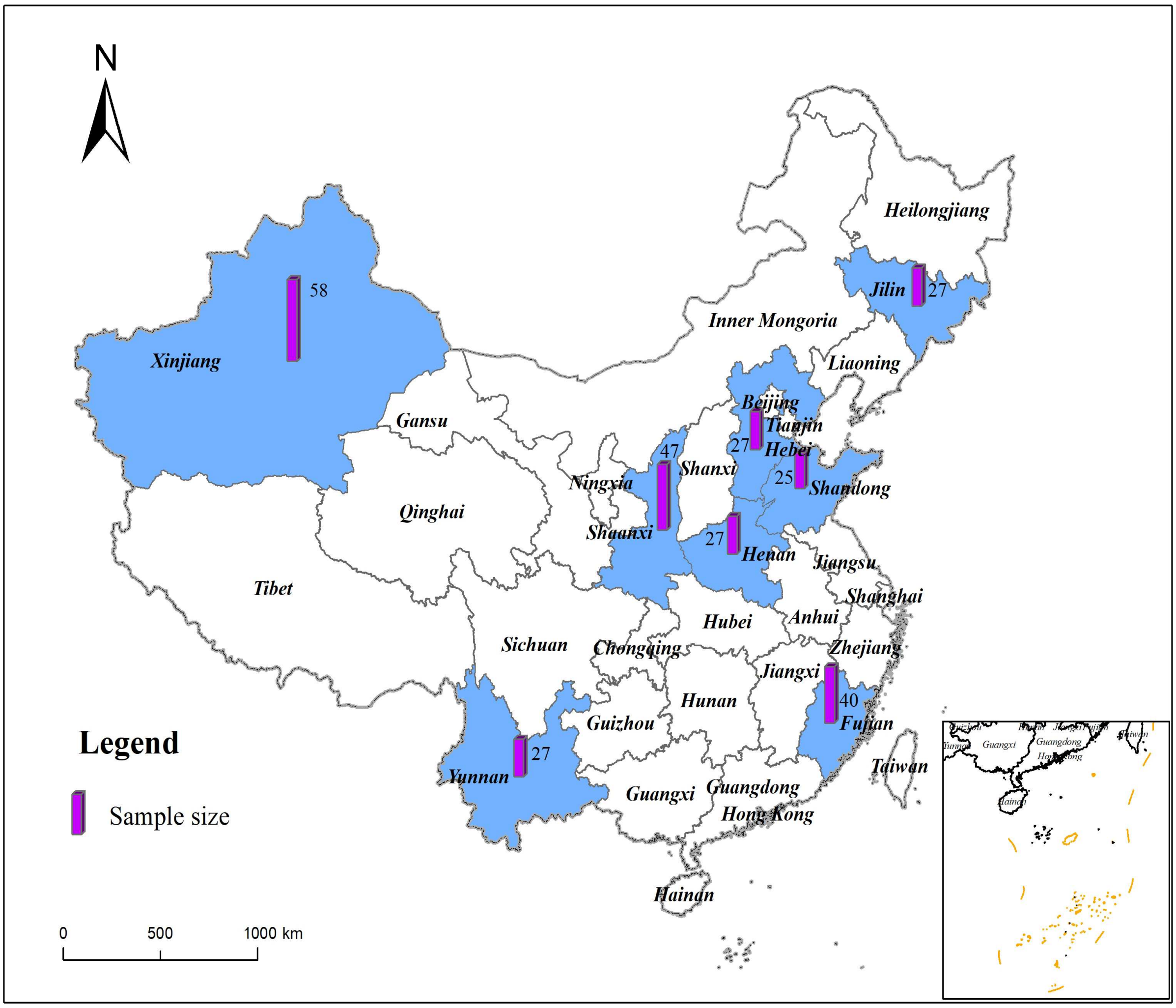

Figure 2. Map of the study area.

3.4. Basic Data Descriptive Statistics

Concerning animal epidemics, the proportion of major epidemic events recognized by the superior government decreased generally from 2012 to 2018, but not year by year, and there was a certain fluctuation between years (Table 3). Therefore, from 2012 to 2018, the incidence of livestock epidemic diseases decreased in the sample area overall but was a persistent threat to local livestock production, and there are significant regional differences (Table 3).

Table 3. Descriptive statistics of the occurrence of the animal epidemic.

Years	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Total**
Number of villages involved	184	193	196	190	168	175	158	1264
Number of villages with a major epidemic events recognized by the government	8	5	4	4	1	3	3	28
Percentage (%)	4.35	2.59	2.04	2.11	0.60	1.71	1.90	2.22
Provinces Name	**Hebei**	**Jilin**	**Fujian**	**Shandong**	**Henan**	**Yunnan**	**Shaanxi**	**Xinjiang**
Sample size	174	159	155	107	134	164	120	251
Number of villages with a major epidemic events recognized by the government	0	1	2	3	0	9	1	12
Percentage (%)	0.00	0.63	1.29	2.80	0.00	5.49	0.83	4.78

The climate variable statistics showed that the average temperature fluctuates upward in sample areas. The maximum and minimum temperatures both increased. The wind speed generally increased too. The humidity and precipitation fluctuated between years without an obvious increase or decrease (Figure 3). In addition, extremely hot weather (>35 °C) showed an increasing trend too (Figure 4). The variation trend of meteorological factors in the sample area is consistent with that of the overall meteorological factors in China, especially the rising trend of temperature and the increasing trend of high-temperature days. It is also consistent with the trend of rising global temperatures. It shows that the selection of sample areas is representative, suitable for the study of the impact of CC on animal diseases, and has practical application value.

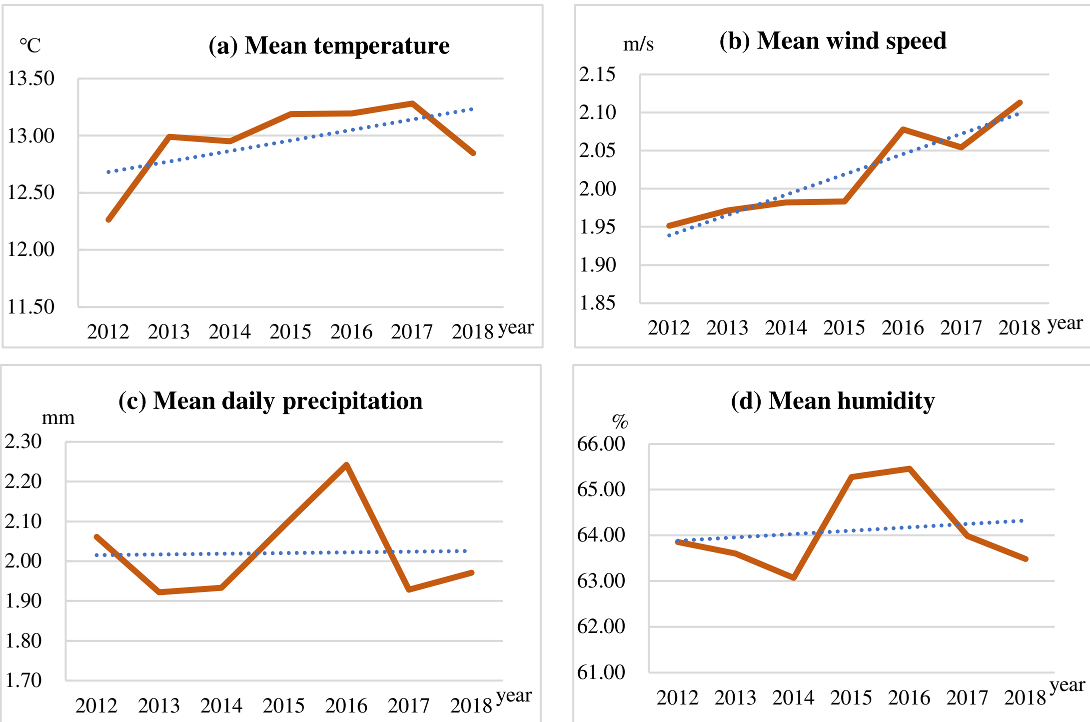

Figure 3. Climate situation "mean temperature, wind speed, daily precipitation, and humidity" from 2012 to 2018. The solid line represents the mean values of temperature, wind speed, daily precipitation, and humidity for each year, while the dotted line represents the trend line for these indicators.

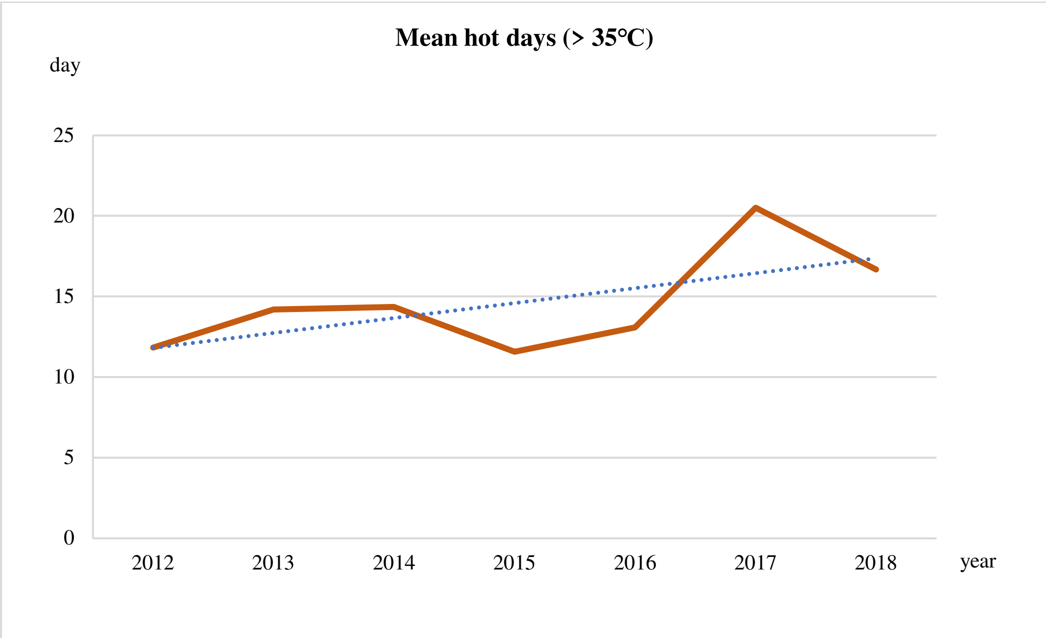

Figure 4. Hot weather from 2012 to 2018. The solid line represents the mean number of hot days (>35 °C) for each year, and the dotted line represents the trend line for mean hot days (>35 °C).

4. Results

4.1. The Influence of Climate Variables on Animal Disease Occurrence

4.1.1. The Influence of Temperature

Univariate regression results show that the regression coefficients of the mean temperature and mean daily minimum temperature are positive and are significant at a significance level of 5% and 1%, respectively, while the regression coefficients of the mean daily maximum temperature are not significant at a significance level of 10%. To examine the effect of extremely hot weather and obtain specific sensitive temperatures, we measured the effect of different temperatures, especially considering the range from 35 °C to 45 °C. The regression results show that the regression coefficients of the days above 37~45 °C are all positive and are significant at a significance level of 10%, and the sensitive temperature may be 37 °C (Table 4). Existing research suggests that increased heat waves will lead to increased heat stress in livestock [45], compromised host immunity [46], and increased heat-related livestock mortality and severe disease [13]. The regression results of this study provide some quantitative support for this point.

4.1.2. The Influence of Precipitation, Humidity, and Wind Speed

The regression coefficient of mean daily precipitation is negative, but not significant at a significance level of 10%. According to the findings of the univariate regression analysis, the regression coefficients of the precipitation anomaly index are negative and are significant at a significance level of 5%. Consequently, the influence of precipitation on animal illnesses could not be represented in average precipitation, but rather in the degree of precipitation variation from typical values. The occurrence of animal illnesses would be negatively impacted by precipitation that is above the average value, which also reflects the features of China's low precipitation. The regression coefficient of mean humidity is negative, but not significant at a significance level of 10%. The regression coefficient of mean wind speed is positive and is significant at a significance level of 5% (Table 5).

Table 4. Regression results of the influence of temperature on the total sample.

Temperature	Occurrence of Animal Major Epidemic Diseases
Mean temperature	0.0206 **
Mean daily minimum temperature	0.0282 ***
Mean daily maximum temperature	0.0106
Number of days with high temperature	
days with >35 °C	0.0007
days with >36 °C	0.0014
days with >37 °C	0.0021 *
days with >38 °C	0.0043 **
days with >39 °C	0.0088 ***
days with >40 °C	0.0120 ***
days with >41 °C	0.0104 ***
days with >42 °C	0.0211 ***
days with >43 °C	0.0176 ***
days with >44 °C	0.0188 ***
days with >45 °C	0.0187 **

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; individual fixed effects and time fixed effects are controlled; The joint tests of the year dummy variables all reject the null hypothesis of no effect at a significance level of 10%.

Table 5. Impact of precipitation, humidity, and wind speed on regression findings.

Precipitation	Occurrence of Animal Major Epidemic Diseases
Mean daily precipitation	−0.0097
Precipitation anomaly index	−0.0462 **
Mean humidity	−0.0015
Mean wind speed	0.0615 **

Note: ** $p < 0.05$; the joint tests of the year dummy variables cannot reject the null hypothesis of no effect in the mean daily precipitation, precipitation anomaly index, and mean humidity regressions at a significance level of 10%; the joint tests of the year dummy variables reject the null hypothesis of no effect in the mean wind speed regression at a significance level of 5%.

4.1.3. Impact of Temperature, Precipitation Anomaly Index, Wind Speed, and Animal Concentration on Regression Findings

With China's fast expansion of animal husbandry, the breeding style of livestock and poultry has altered dramatically. Increased large-scale centralized breeding is one significant symptom. The proportion of villages in our study sample region with significant livestock and poultry breeding grounds increased from 2012 to 2018, accounting for 22.68% in 2012, 26.16% in 2018, and 29.78% in 2017. Given that concentrated farming may influence the likelihood and severity of animal disease transmission and disease control efficiency, the concentration extent of livestock was used as a control variable to investigate the impact of climate factors on the occurrence of animal epidemics in China. The concentration extent of livestock was defined as the presence of centralized livestock and poultry breeding sites (1 = yes, 0 = no). Univariate regression results showed that the regression coefficient of livestock concentration is positive and significant at a 1% significance level. In multivariate analysis, potential variable interactions may have an impact on the regression results. Considering that the correlation coefficient between mean temperature and mean daily minimum temperature is as high as 0.9941, the occurrence of animal diseases is more susceptible to extreme temperature, so the mean daily minimum temperature is retained in the multivariate regression, and the mean daily minimum temperature is not included in the multivariate regression to avoid multicollinearity. For high-temperature days, days above 35 °C to 45 °C are also examined here, and a margin of 39 °C is determined based on the significance level (regression coefficients below 39 °C are not significant at a significance level of 10%, while regression coefficients above 39 degrees Celsius are significant). When livestock concentration is included as a control variable in the multivariate model, the regression coefficients of mean daily minimum temperature, days above 39 °C, precipitation anomaly index, and mean wind speed remained significant at a 10% significance level, and the direction of the regression coefficients was consistent with univariate analysis (Table 6).

4.2. The Influence of Climate Variables on Animal Disease Occurrence in Subsamples

4.2.1. The Influence of Temperature

The regression results show that the regression coefficients of the mean temperature are not significant in the north, northwest, and south regions, and in Jilin, Shandong, and Yunnan, but are significantly negative in Shaanxi and Fujian. The regression coefficients of the mean daily minimum temperature are not significant in the northwest and south areas, and in Jilin, Yunnan, and Fujian, but are significantly positive in north and Shandong, and significantly negative in Shaanxi. The regression coefficients of the mean daily maximum temperature are not significant in the north, northwest, and south regions, and in Jilin, Shaanxi, and Yunnan, but are significantly negative in Shandong and Fujian. The regression coefficients of high-temperature days are significantly negative in Shandong and northwest areas, which are consistent with the overall sample, but the sensitive temperatures were different: 39 °C in Shandong and 38 °C in Northwest (Xinjiang). The regression coefficient of days above 35 °C in Shandong is significantly negative at a significance level of 10%, which is inconsistent with expectations (Table 7).

4.2.2. The Influence of Precipitation, Humidity, and Wind Speed

The analysis findings demonstrate that regression coefficients of mean daily precipitation are not significant at a significance level of 10% for any subsample and total sample. The regression coefficient of the precipitation anomaly index significantly is negative in the northwest (#Xinjiang), which is consistent with the overall sample. The regression coefficients of mean humidity are significantly negative in Shandong and Shaanxi. The regression coefficient of mean wind speed is significantly positive in the north, which is consistent with the overall sample (Table 8).

Table 6. Regression results from the influence of extremely hot weather, precipitation anomaly index, and concentration of livestock.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean daily minimum temperature	0.0282 *** (0.0096)					0.0253 ** (0.0100)	0.0263 *** (0.0100)
Days with >39 °C		0.0088 *** (0.0025)				0.0059 ** (0.0026)	0.0055 ** (0.0026)
Precipitation anomaly index			−0.0462 ** (0.0185)			−0.0376 ** (0.0195)	−0.0374 * (0.0194)
Mean wind speed				0.0615 ** (0.0281)		0.0668 ** (0.0283)	0.0687 ** (0.0282)
Concentration of livestock					0.0386 *** (0.0141)		0.0379 *** (0.0139)
Constant	−0.1612 ** (0.0721)	0.0362 *** (0.0100)	0.0232 *** (0.00349)	−0.0731 (0.0563)	0.0389 ** (0.1007)	−0.2771 *** (0.0991)	−0.2970 *** (0.0993)
Observations	1264	1264	1264	1264	1262	1264	1262
R-squared(within)	0.0190	0.0230	0.006	0.0153	0.0181	0.0365	0.0438
Number of villages	268	268	268	268	268	268	268
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	No	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; the time fixed effects are controlled in the models where the joint tests of the year dummy variables reject the null hypothesis of no effect at a significance level of 10%.

Table 7. Regression results of the influence of temperature in the subsamples.

Temperature	Total Sample	North	Jilin	Shandong	Shaanxi	Northwest (Xinjiang)	South	Yunnan	Fujian
Mean temperature	0.0206 **	0.0179	0.0086	−0.0522	−0.0441 *	0.0183	−0.0037	−0.0091	−0.0760 **
Mean daily minimum temperature	0.0282 ***	0.0246 *	0.0094	0.2500 **	−0.0611 *	0.0159	0.0031	0.0023	−0.0379
Mean daily maximum temperature	0.0106	0.0082	0.0069	−0.0506 *	−0.0277	0.0230	−0.0226	−0.0065	−0.0434 *
Number of days with high temperature									
Days with >35 °C	0.0007	−0.0009	−0.0016	−0.0141 *	−0.0025	0.0033	0.0014	0	0.0007
Days with >36 °C	0.0014	−0.0002	−0.0021	−0.0014	−0.0003	0.0035	0.0017	—	0.0007
Days with >37 °C	0.0021 *	−0.0007	0	0.0003	−0.0023	0.0042	0.0007	—	−0.0002
Days with >38 °C	0.0043 **	0.0002	0	0.0097	−0.0010	0.0062 *	−0.0033	—	−0.0046
Days with >39 °C	0.0088 ***	−0.0022	0	0.0620 *	−0.0100	0.0100 **	−0.0167	—	−0.0198
Days with >40 °C	0.0120 ***	−0.0163	0	—	−0.0233	0.0123 ***	—	—	—
Days with >41 °C	0.0104 ***	−0.0001	0	—	0	0.0099 *	—	—	—
Days with >42 °C	0.0211 ***	—	—	—	—	0.0196 **	—	—	—
Days with >43 °C	0.0176 ***	—	—	—	—	0.0164 **	—	—	—
Days with >44 °C	0.0188 ***	—	—	—	—	0.0177 *	—	—	—
Days with >45 °C	0.0187 **	—	—	—	—	0.0169	—	—	—

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; the joint tests of the year dummy variables reject the null hypothesis of no effect in the north and south subsamples regressions at a significance level of 10%, so time fixed effects are controlled in these regressions; the dependent variables of Hebei and Henan samples lacked variation and were omitted in the regression.

Table 8. Regression results of the influence of precipitation, humidity, and wind speed in the subsamples.

Precipitation	Total Sample	North	Jilin	Shandong	Shaanxi	Northwest (Xin-jiang)	South	Yunnan	Fujian
Mean daily precipitation	−0.0079	−0.0108	−0.0321	−0.0071	−0.0539	−0.1212	−0.0066	−0.0193	−0.0041
Precipitation anomaly index	−0.0477 **	−0.0216	−0.0572	−0.0112	−0.0920	−0.0875 *	−0.0227	−0.0584	−0.0202
Mean humidity	−0.0000	−0.0021	−0.0010	−0.0210 **	−0.0623 **	0.0004	−0.0019	−0.0021	−0.0015
Mean wind speed	0.0615 **	0.0552 *	0.0099	0.0037	−0.0568	0.0900	0.0611	0.0667	0.1586

Note: ** $p < 0.05$, * $p < 0.1$; the joint tests of the year dummy variables reject the null hypothesis of no effect in the north and south subsamples regressions at a significance level of 10%, so time fixed effects are controlled in these regressions; the dependent variables of Hebei and Henan samples lacked variation and were omitted in the regression.

5. Discussions

This study attempts to apply a quantitative analysis method to study the relationship between climate factors and animal diseases, to understand the impact of CC on the occurrence of animal diseases, and then to provide support for animal disease management practices to better cope with the challenge of CC.

5.1. Climate Factors and Animal Diseases

CC can have a major impact on the spread of animal diseases, and there is a lot of research looking at that, but there are few quantitative studies. The relationship between CC and animal diseases is complicated. This study attempts to apply the quantitative analysis method in the study of the relationship between CC and animal diseases, to obtain specific impacts and provide empirical support for related practices.

(1) Temperature: in the existing research, temperature is the most concerned climate factor. An increase in warm spells and heat waves would bring increased heat stress on livestock [45] and would suppress feed intake, milk production, reproductive performance, immunity, and endocrine function [47]. Diseases previously confined to the tropics are now spreading to other previously cooler regions [23]. In addition to the effect of high temperatures, studies have also looked at the effect of low-temperature days [19,45]. It is suggested that a higher minimum temperature may lead to a reduction in the frequency and severity of cold stress events. This study focused on the influence of temperature, especially the number of days with high temperatures. Using panel data from 278 villages in China over 7 years, a regression analysis was conducted, and it was found that the number of days with high temperatures had a significant positive impact on the occurrence of major animal diseases, which was consistent with the conclusion of previous studies. The regression results of this study show that the increase in minimum temperature will increase the incidence of disease, which is inconsistent with previous studies.

(2) Precipitation: floods have been linked to an increase in vector transmission and infectious diseases [45]. RVF outbreaks often occur following periods of above-normal precipitation [48]. This study shows that the precipitation anomaly index has a significant negative effect on the occurrence of major animal diseases, which seems to be inconsistent with previous studies. It is possible that the impact of precipitation varies from region to region and needs further examination.

(3) Wind speed: Endo N and Eltahir EA [49] have looked at the effect of wind on malaria around reservoirs and found it can be substantial. They indicate that wind should be considered as a crucial factor in the transmission of various diseases, not just those that are air-borne, because it could modulate the dynamics of different vectors and pathogens. Joel H Ellwanger and José A B Chies argued wind's capacity to carry and disperse signal molecules (e.g., CO_2), or other as yet unidentified features, making it a more important factor in the environmental component of the One Health concept [50]. Campylobacter spp. prevalence increases in poultry on farms with higher average wind speeds in the seven days preceding sampling [51]. The regression results in this study indicate that average wind speed shows a significant positive effect on the occurrence of major animal diseases.

It shows that wind is an important climatic factor in studying the effects of climate change on animal diseases.

(4) Humidity: the average humidity results show significant effects in some regions, but not in the total samples. Therefore, the effects of humidity need to be observed and studied further.

(5) Regional differences: in the regression analysis of the subsamples, it was found that the regression coefficients and the significance of each climate factor showed significant regional differences, which may be related to the differences in climate characteristics, ecological environment, and animal breeding practices in each region. In addition, compared with the total sample, the number of subsamples is relatively small, which will also affect the regression results.

5.2. Limitation

This study has some limitations.

(1) Data: due to the climate system complexity and the many factors that contribute to the outbreak of animal diseases, it may be challenging to obtain comprehensive and accurate data for both variables. CC is a relatively recent phenomenon, and there is a lack of long-term data on the impact of CC on animal diseases. This could limit the ability to draw robust conclusions about the relationship between the two variables. In addition, the sample size may also affect the results.

(2) Causation: although there is a correlation between CC and the outbreak of animal diseases, it is difficult to establish a direct cause-and-effect relationship between the two variables.

(3) Regional factors and species differences: the relationship between CC and animal diseases may vary depending on the geographic location and the specific species of animals being studied. Therefore, the findings of the study may not be generalizable to other regions or animal populations. In this research, different animals and diseases are mixed; species differences and disease types may have influenced the results.

(4) Other factors: many other factors may play a role in the spread of animal diseases, such as changes in land use, animal husbandry practices, and the movement of people and animals, which can also influence the spread of diseases. The outbreak of animal diseases may be influenced by a range of other factors, such as the use of antibiotics, changes in animal trade, and human behavior. These confounding variables could limit the ability to attribute changes in disease patterns solely to CC.

5.3. Future Directions

In the future, we hope that more in-depth research can be carried out.

(1) Impact mechanism verification: this study mainly focused on the empirical analysis of the relationship between climate variables and animal diseases based on data, and the analysis and verification of the specific mechanism of action could be further expanded and deepened in the future.

(2) Obtain and apply better data sets: the data used in this study were at the village level. A study in China found that the meteorological factors affecting diseases are different in different seasons. If there is an opportunity to obtain the data from farmers, the relevant results can be further tested. In addition, in this research, all animal diseases are included together. If we can distinguish different animals, different diseases, and different seasons, the influence of climate variables on different animal species and diseases can be more specifically investigated. The improvement of the government's surveillance and data collection system for animal diseases can provide favorable conditions for empirical research on animal diseases. If we can collect data over a longer time span, we can obtain more robust conclusions.

(3) Improvement of quantitative models: if a more scientific model can be used to verify the causal relationship between climate factors and animal diseases and to consider the

possible effects of other factors, it will help to better understand the relationship between CC and animal diseases.

6. Conclusions

This study utilized village-level panel data to investigate the influence of climate variables on the occurrence of animal diseases in China. The findings of this study demonstrate that quantitative analysis can offer novel methods and insights for examining the relationship between CC and animal diseases, while also providing more direct recommendations for practical application. The empirical analysis in this study revealed a discernible correlation between the incidence of animal diseases and several variables, including average temperature, average daily minimum temperature, the number of high-temperature days, precipitation anomaly index, wind speed, and other factors. Particularly, an increase in temperature exhibited a significant promoting effect on the occurrence of animal diseases. Given that the occurrence of a major animal epidemic event can have a profound impact on animal product supply and the livelihoods of farmers, and considering the upward trend in temperatures observed in China, this may pose substantial challenges for the prevention and control of animal diseases. Therefore, it is imperative to contemplate the implementation of targeted intervention and prevention measures to mitigate potential losses. It is important to acknowledge that research faces challenges related to data, models, regional and species variations, and other unobserved or unaccounted factors, especially when attempting to establish causal links between CC and animal diseases. Consequently, the impact of CC on animal diseases warrants sustained attention, and future research endeavors should delve deeper into this subject.

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