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ORIGINAL ARTICLE

Spatiotemporal analysis of reported classical swine fever outbreaks in China (2005–2018) and the influence of weather

Xiao Lu | **Michael P. Ward**

Sydney School of Veterinary Science, The University of Sydney, Camden, Australia

Correspondence
Michael P. Ward, Sydney School of Veterinary Science, The University of Sydney, Camden, NSW 2570, Australia.
Email: michael.ward@sydney.edu.au

Funding information
Sydney School of Veterinary Science

Abstract

Classical swine fever (CSF) is a viral disease that causes enormous economic losses in the swine industry in endemic countries including China. The aims of the current study were to describe the spatial distribution of annual CSF reports in China from 2005 to 2018, identify spatiotemporal clusters of annual CSF reports during this time period and to investigate the correlations between climate factors (rainfall, wind speed, temperature, vapour pressure and relative humidity) and the occurrence of CSF outbreaks. The strongest (Moran's index > 0.19), significant ($p < .05$) spatial clustering of reported outbreaks was observed during the first 4 years of the study period. This clustering was apparent in the four southern provinces of Guizhou, Guangxi, Guangdong and Yunnan. Five of the six significant ($p \leq .0001$) spatiotemporal clusters occurred during the period 2005–2012. These were widely dispersed, with four clusters persisting for only 1 or 2 years, whereas two clusters (Jiangxi and Yunnan) persisted for 8 and 7 years, respectively. As a result of implementation of a national animal disease control plan and increasing coverage of vaccination, CSF outbreaks in China have generally been controlled and reduced, becoming sporadic in most provinces by 2018. We also confirmed that low relative humidity and high wind speed were significant weather variables associated with the occurrence of CSF. Furthermore, our study has confirmed that CSF is still endemic in some Chinese provinces, and we recommend that the national CSF control protocol be updated and standardized.

KEYWORDS
China, classical swine fever, epidemiology, pig, virus

1 | INTRODUCTION

Classical swine fever (CSF) is a highly contagious porcine disease caused by a single-stranded, enveloped RNA virus, classical swine fever virus (CSFV), a *Pestivirus* in the *Flaviviridae* family (Blome et al., 2017; Schulz et al., 2017). CSF is a World Organisation for Animal Health (OIE) listed disease with both high mortality and morbidity (OIE, 2021). As it causes enormous production loss in the swine industry globally, early diagnosis and timely disposal of the affected animals are necessary (Moennig, 2015; Moennig & Becher, 2015; Moennig et al., 2003; Zhou, 2019). Depending on the virulence of the viral sub-genotypes, the clinical outcomes of CSF vary from the chronically compromised, persistent shedders of the virus to rapid death caused by acute multi-systemic conditions (Blome et al., 2017; Moennig et al., 2003; Schulz et al., 2017; Zhou, 2019). The typical acute clinical signs of CSF include acute onset gastrointestinal and respiratory signs, pyrexia, loss of appetite, lethargy, generalized haemorrhage or neurological signs (Ministry of Agriculture and Rural Affairs, 2006; Schulz et al., 2017). In combination with epidemiological information (e.g. species and signalment), immunization history and pathological changes (e.g. haemorrhage of multiple organs), these clinical signs are considered to be the most direct, rapid evidence to make a diagnosis (Ministry of Agriculture and Rural Affairs, 2006; Moennig & Becher, 2015; Zhou, 2019). However, the clinical signs of CSF overlap with other differential diagnoses (e.g. African swine fever, ASF; porcine reproductive and respiratory syndrome, PRRS), and laboratory diagnostic tests (immunological and molecular tests as well as pathogen isolation) are required for the definite diagnosis (Moennig & Becher, 2015; Zhou, 2019).

Historically, the transmission route of CSFV in the case of incursions and outbreaks has often been unclear and its re-emergence has been observed in countries formerly confirmed CSF-free status (Moennig, 2015; Moennig et al., 2003). The transmission of CSFV can be either direct or indirect. While transplacental vertical transmission is possible (Blome et al., 2017; Kaden et al., 2008; Ribbens et al., 2004; Schulz et al., 2017), horizontal transmission via direct contact between infected and susceptible pigs is the most common route (Ribbens et al., 2004; Schulz et al., 2017). Wild boars have been shown to act as the main vector and reservoir of the virus in some situations, complicating complete eradication of CSF in regions including Europe and Asia (Blome, 2019; Kamakawa et al., 2006; Moennig, 2015; Ribbens et al., 2004). According to historical reports of CSF epidemics in Germany between 1990 and 1998, more than 60% of the outbreaks in domestic pigs resulted from direct and indirect spill-over from wild porcine populations (Fritzemeier et al., 2000). Other identified transmission routes include swill feeding containing contaminated pig meat (Edwards, 2000), mechanical transmission by fomites (vehicles, farm personnel and uncleaned environment) (Blome et al., 2017) and short-distance airborne transmission under experimental conditions (Weesendorp et al., 2009). The role of biological vectors, including arthropods and rodents, in CSFV transmission is not supported by previous studies (Kaden et al., 2003; Ribbens et al., 2004).

The prevention or the minimization of CSF impacts can be achieved by the management of the farm environment and prophylactic vaccination (Blome et al., 2017; Schulz et al., 2017). Although culling of CSF infected pigs is a common measure in non-endemic countries when outbreaks occur, compulsory vaccination plans remain the preferred preventive strategy in countries including China (Zhou, 2019). In terms of husbandry risk factors, an influence of environmental temperature and the regional density of both wild and domestic pig populations on viral survival and transmission has been identified (Luo et al., 2014; Moennig, 2015; Moennig et al., 2003; Weesendorp et al., 2008). In the same study in which Weesendorp et al. performed experiments on the airborne transmission of CSFV, they also found a potential negative association between wind speed and aerosolized CSFV, and hypothesized a mechanical stress to CSFV caused by high wind speed (Weesendorp et al., 2008). Moreover, it is notable that the condition is endemic in tropical countries, for example, south-eastern Asian countries including Cambodia, Laos and Vietnam (Blacksell et al., 2004; Kamakawa et al., 2006; Zhou, 2019), where the climate is characterized by high average temperature as well as high relative humidity. The relationship between climate factors—including ambient humidity and wind speed—and the occurrence of CSF remains to be studied.

In China, the world's largest pork-producing country with approximately half of the global pig production (Zhou, 2019), pork comprises 70% of the domestic meat consumption and therefore is of great economic and sociological importance (Liu et al., 2021; The State Council of the People's Republic of China, 2019). Since its first occurrence in the early 20th century, CSF has been endemic in many Chinese provinces and has remained a concern to the pig industry (Luo et al., 2014). Benefiting from the recent establishment of the Veterinary Bureau of the Ministry of Agriculture and Rural Affairs in 2004 and subsequent development of veterinary science in China (Zhang, 2019), a national protocol for CSF prevention and control has been implemented since 2006 to reduce related economic losses and achieve regional eradication (Ministry of Agriculture and Rural Affairs, 2006). The protocol prioritized vaccination as the primary preventive measure and stated the comprehensive, compulsory immunization policy of full vaccination of pigs with live attenuated registered C-strain vaccines (Luo et al., 2014; Ministry of Agriculture and Rural Affairs, 2006; Zhou, 2019). In 2012, the State Council of the People's Republic of China published the National Medium- and Long-Term Animal Disease Control Plan and further emphasized the importance of eradicating CSF from mainland China, classified CSF as one of the Class I infectious animal diseases and proposed the goal of eliminating CSF in all source breeder farms by 2015, and all breeder farms across the nation by 2020 (The State Council of the People's Republic of China, 2012). However, as indicated in previous literature, sporadic CSF outbreaks still occur each year and the endemic status in some parts of China has persisted even after the authority's control plan (Luo et al., 2014; Zhou, 2019).

In contrast, according to the Animal Epidemic Prevention Law of the People's Republic of China which was first enacted in 1997 (The State Council of the People's Republic of China, 2021), veterinary surveillance and monitoring systems and the conduct of animal epidemic prevention and control measures are highly community-based and highly flexible across regions. Following the strategies and legislation published by the State Council, provincial (including provinces, autonomous regions and municipalities) government departments of agriculture and rural affairs establish and maintain diagnostic laboratories for the corresponding administrative districts; plan, organize, approve and supervise animal epidemic prevention and control activities of the subordinate governments; assess the outcomes of the plans conducted; report the disease outbreaks identified within the administrative districts and provide technological support and personnel when animal epidemics have been detected. Most animal epidemic prevention and control measures are performed at individual-, subdistrict- or township-level and organized by the villagers' committees or neighbourhood committees under the supervision of county-level or higher authorities (The State Council of the People's Republic of China, 2012, 2021). The reporting system is limited to each province, and the reports collected by the provincial departments are then submitted to the state level for publication (The State Council of the People's Republic of China, 2021).

In recent years, the ongoing epidemic of ASF and the urgent need to reduce environmental pollution released from swine production in China have become the main topics of pig disease research. This has stimulated the re-evaluation of the pig industry and the decision to re-structure it with stricter animal health regulations (The State Council of the People's Republic of China, 2019; Zheng et al., 2021). However, CSF has not been eradicated from mainland China and its importance should not be neglected. Recent CSF research in China has substantially focused on the molecular aspects of virus control or the development of new marker vaccines and was either geographically limited to small- or medium-scale investigations or performed under laboratory conditions (Gong et al., 2016; C. Liu et al., 2018; Xia et al., 2016; Zhang et al., 2018). The last comprehensive study that investigated the spatial distribution of CSF on a national basis was published in 2001 (Tu et al., 2001), and discussion on the spatiotemporal patterns of CSF outbreaks in the past two decades is lacking.

The World Animal Health Information System (OIE-WAHIS) is a timely, publicly accessible animal disease monitoring system maintained by the OIE (Mur et al., 2019). In this study, we retrieved CSF outbreak reports data from 1 January 2005 to 31 December 2018 from the People's Republic of China. The objectives of our study were as follows: (1) to describe the spatiotemporal distribution and potential clustering of CSF in China and (2) to investigate the association between weather (temperature, relative humidity, wind speed, rainfall and vapour pressure) and the occurrence of CSF.

2 | METHODS

2.1 | Data preparation

We retrieved the provincial count of reported new CSF outbreaks per month in China (from January 2005 to December 2018) from the OIE-WAHIS (OIE, 2020), from which we calculated the annual data.

The monthly surface climate data were downloaded from the China Meteorological Data Service Centre (CMDC) (CMDC, 2021). For provinces in which the data were measured at several stations, the provincial mean value of all climate parameters was calculated and used in further analyses.

Although we were unable to find published provincial numbers of herds or production sites, the annual provincial pig stock size is published by the Chinese Ministry of Agriculture and Rural Affairs and was accessed from the CEIC database (Ministry of Agriculture and Rural Affairs, 2020). The domestic pig population size data were only used to make comparisons across provinces via provincial groupings. For each province, the mean pig population size was calculated over the 14-year study period.

In terms of risk factors facilitating transmission of CSFV, high density of the pig population and temperature have been identified in multiple studies (Fonseca-Rodríguez et al., 2020; Koenen et al., 1996; Porphyre et al., 2017; Weesendorp et al., 2008; Wijnker et al., 2008). To minimize the effect of pig population density and temperature when making comparisons, as well as to reduce the number of provinces involved in the analyses, we included provinces with at least one reported CSF outbreak during the study period and grouped them based on two sets of criteria: pig population size and climate zone. The grouped data were then analyzed by cross-correlation functions to determine whether climate factors, including but not limited to temperature, are associated with the occurrence of CSF outbreaks.

2.2 | Population grouping

As mentioned above, higher population density within both the herd and the region leads to higher risk of CSF occurrence (Fritzemeier et al., 2000; Moennig, 2015). We classified the provinces into four population groups defined by lower quartile, median and upper quartile of the national mean pig population sizes to adjust the analyses for the potential effect of different pig population densities across provinces.

1. Group I: Mean pig population size is less than the first quartile ($n < 4019$ thousand pigs), which includes five provincial-level administrative divisions (Ningxia, Qinghai, Shanghai, Tianjin and Xinjiang).
2. Group II: Mean pig population size is greater than or equal to the first quartile and less than the median ($4019 \leq n < 13{,}490$ thousand), which includes seven provinces (Fujian, Gansu, Hainan, Jilin, Shaanxi, Shanxi and Zhejiang).
3. Group III: Mean pig population size is greater than or equal to the median and less than the upper quartile ($13{,}490 \leq n < 20{,}608$ thousand), which includes six provinces (Anhui, Chongqing, Guizhou, Heilongjiang, Jiangsu and Jiangxi).
4. Group IV: Mean pig population size is greater than the upper quartile ($n > 20{,}608$ thousand), which includes eight provinces (Guangdong, Guangxi, Hebei, Henan, Hubei, Hunan, Shandong and Yunnan).

2.3 | Climate grouping

In the housing environment, the survival of CSFV is favoured under thermal conditions which are cooler than the ambient temperature (Weesendorp et al., 2008; Wijnker et al., 2008). Similarly, to adjust for the impact of temperature on CSF occurrence, provinces were classified into five climate groups based on the main climate groups of the Köppen–Geiger climate classification system (Rubel & Kottek, 2010) as follows:

1. Group D (continental climate): Heilongjiang, Jilin,
2. Group BD (both continental and dry climates are present within the province): Heibei, Tianjin, Shanxi, Shaanxi, Xinjiang, Ningxia and Gansu,

3. Group E (polar and alpine climates): Qinghai,
4. Group C (temperate climate): Henan, Shandong, Jiangsu, Anhui, Hubei, Chongqing, Guizhou, Guangxi, Guangdong, Yunnan, Shanghai, Zhejiang, Jiangxi, Hunan and Fujian,
5. Group A (tropical climate): Hainan.

2.4 | Mapping and spatial statistics

The shapefiles of Chinese administrative district borders were adapted from the map published by the National Platform for Common Geospatial Information Services (National Platform for Common Geospatial Information Services, 2020). Mapping and two spatial analyses were performed in ArcGIS desktop 10.7 (ESRI, 2019). Descriptive mapping of the annual count of CSF reports per province was conducted. To verify and visualize the clustering and randomness of the outbreaks' distribution, spatial autocorrelation (Global Moran's Index) test as well as cluster and outlier analysis (Anselin Local Moran's Index) were conducted on a yearly basis excluding Heilongjiang since this province is spatially isolated from the rest of the locations. The year 2017 was also excluded since CSF outbreaks were only reported in two provinces, and the data were insufficient for analysis.

The retrospective spatiotemporal permutation model (Kulldorff et al., 2005) was used with 25% maximum spatial cluster size in SaTScan (version 9.7) (SaTScan, 2021) to identify spatiotemporal clusters during the study period.

2.5 | Cross-correlation functions

From the available weather factors, we selected the calculated mean values of daily rainfall (mm/day), average wind speed (m/s), average vapour pressure (i.e. absolute humidity) (HPa), average temperature (°C), average minimum temperature (°C), average maximum temperature (°C) and minimum relative humidity (%) to perform cross-correlation analysis with reported CSF outbreaks (IBM SPSS Statistics 24.0). The tests were performed at the group level for both pig population and climate groups.

3 | RESULTS

During the 14-year period, 5385 CSF reports from 26 Chinese provinces were made. Among the provinces included, CSF was most frequently reported from Guangxi (n = 1357), followed by Guangdong (n = 859) and Guizhou (n = 855) in southern China. Chongqing, Hebei, Shandong and Shanghai were provinces in which CSF outbreaks were only reported in 1 year during the period 2005–2018. Annual choropleth maps of CSF reports are included in Appendix I.

3.1 | Mapping, spatial statistics and spatiotemporal permutation analysis

The autocorrelation analysis identified the presence of significant spatial clustering of CSF outbreak reports from 2005 to 2018 (Table 1). Clusters were further confirmed by the local indicator of spatial autocorrelation (LISA) analysis (Figure 1; the complete set of annual maps of the LISA analysis is shown in Appendix II). The permutation model identified six significant spatiotemporal clusters (Table 2): (1) Shanghai, Zhejiang and Jiangsu (2005–2006), (2) Guangdong (2005–2007), (3) Jiangxi (2005–2012), (4) Fujian (2007–2009), (5) Henan, Hubei, Anhui, Shanxi and Shaanxi (2011–2012) and (6) Yunnan (2012–2018).

Throughout the study period 2005–2018, the distribution of provincial annual CSF reports was relatively consistent and stable, with a distinct overall decline in the number of CSF reports (Appendix I). CSF reports were most densely distributed during the first four years (2005–2008) (Table 1). Prior to the implementation of the new national animal disease control plan in 2012 (The State Council of the People's Republic of China, 2012), the risk of CSF outbreaks was significantly higher ($p < .05$) in southern and southwest provinces, including Guangdong, Guangxi and Guizhou, compared to other provinces. Despite being adjacent to the large southern China cluster where CSF outbreaks were regularly reported, Yunnan was a province with lower CSF outbreak risk compared to its neighbouring provinces (Guangdong, Guangxi and Guizhou) from 2006 to 2010. Similarly, in 2005 the risk of CSF occurrence was significantly lower in Hainan, which is geographically separated from Guangdong by the Qiongzhou Strait. In 2005 and 2006, Hunan (the province located north of both Guangxi and Guangdong) was also identified as an outlier with fewer CSF reports.

For the other provinces of China, the occurrence of CSF appeared random, and CSF outbreaks were relatively common and endemic during the pre-2012 period. Although the LISA analysis did not identify other significant spatial clusters or outliers, the permutation model suggested high outbreak report counts within eastern Chinese provinces during the same timeframe (Shanghai, Zhejiang, Jiangsu, Jiangxi and Fujian). In contrast, CSF reports from central China (Gansu, Ningxia, Shaanxi and Shanxi) and the highly urbanized Tianjin area were significantly fewer than the national average.

Since 2012, the national animal health control plan effectively reduced the occurrence of CSF in most Chinese provinces, and the regional eradication goal was achieved in these provinces (e.g. the coastal provinces including Jiangsu, Shanghai, Zhejiang, Fujian and Guangdong) with no CSF reports recorded in the OIE-WAHIS database from 2012 to 2018.

In the provinces in which infrequent epidemics persisted, the occurrence of CSF outbreaks became more random and sporadic in contrast to the pre-2012 situation. It is also interesting that a low number of CSF reports were made in Gansu every year from 2012 to 2016, as well

TABLE 1 The spatial autocorrelation (Global Moran's Index) analyses of reported classical swine fever outbreaks in China (excluding Heilongjiang), 2005–2018. Insufficient reports occurred in 2017, and therefore this year was excluded

Year	Moran's index	Expected index	Variance	*z*-Score	*p*-Value
2005	0.298	−0.056	0.0137	3.0168	.0026
2006	0.342	−0.050	0.0105	3.8301	.0001
2007	0.188	−0.056	0.0104	2.3814	.0172
2008	0.243	−0.059	0.0127	2.6782	.0074
2009	0.194	−0.067	0.0178	1.9512	.0510
2010	0.116	−0.067	0.0091	1.9130	.0558
2011	0.033	−0.083	0.0153	0.9432	.3456
2012	−0.286	−0.167	0.1084	−0.3633	.7164
2013	−0.309	−0.200	0.1311	−0.3024	.7624
2014	−0.985	−0.250	0.2019	−1.6363	.1018
2015	−0.081	−0.200	0.1621	0.2963	.7670
2016	0.076	−0.333	0.2056	0.9022	.3670
2018	−0.020	−0.125	0.0218	0.7083	.4788

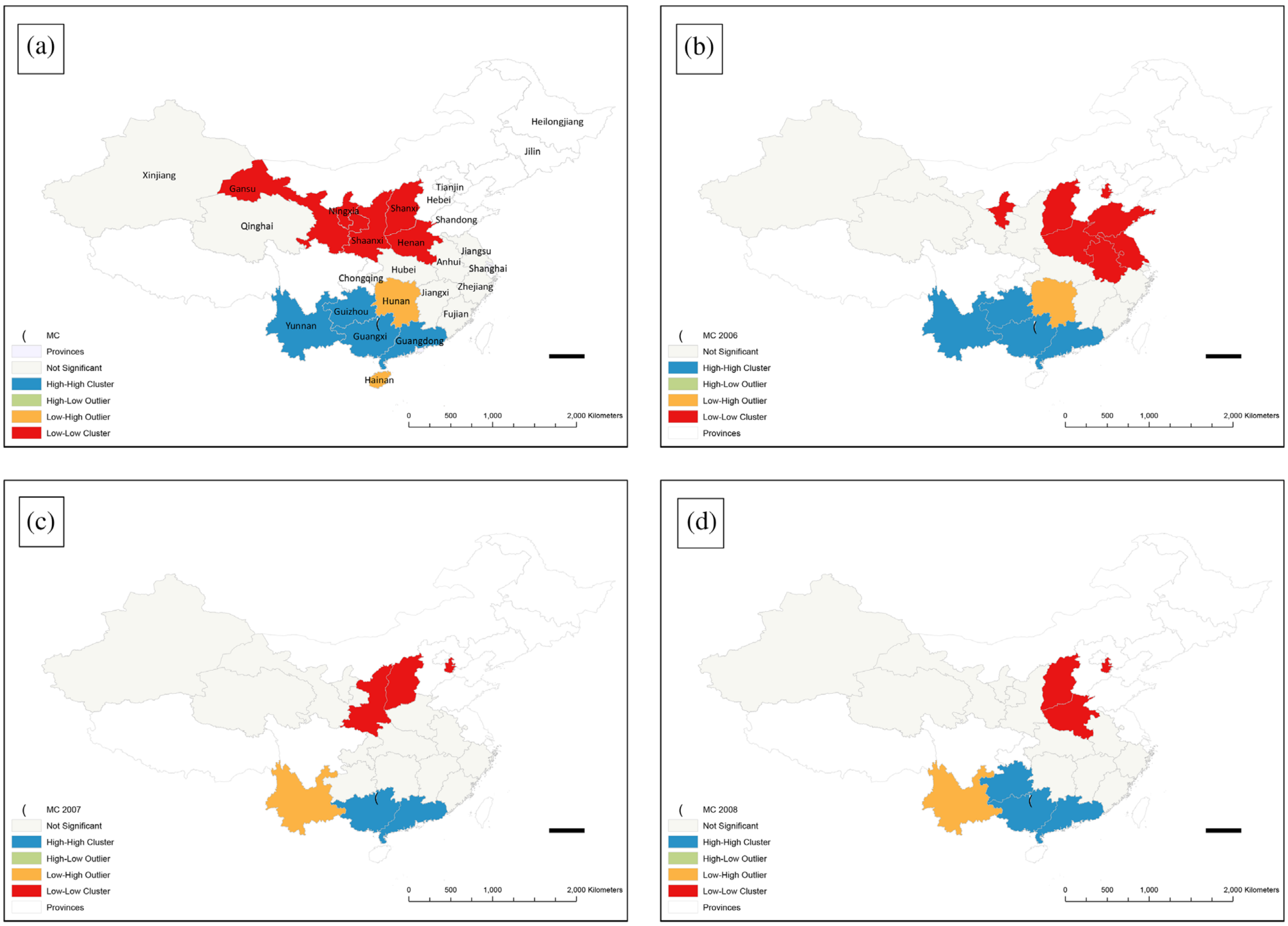

FIGURE 1 Spatial clusters (high–high and low–low) and outliers (high–low and low–high) of annual counts of classical swine fever reports per Chinese province in 2005 (a), 2006 (b), 2007 (c) and 2008 (d). The local indicator of spatial autocorrelation was used for statistical analysis. MC: Median centre of the reports

TABLE 2 Spatiotemporal clusters of classical swine fever (CSF) outbreaks identified by retrospective permutation test (25% maximum spatial cluster size) in China from 2005 to 2018

Period	Provinces	*p*-Value
2005–2006	Shanghai, Zhejiang, Jiangsu	.0001
2005–2007	Guangdong	<.0001
2005–2012	Jiangxi	<.0001
2007–2009	Fujian	<.0001
2011–2012	Henan, Hubei, Anhui, Shanxi, Shaanxi	<.0001
2012–2018	Yunnan	<.0001

as 2018, with CSF reports occasionally from the bordering provinces (Ningxia in 2016 and 2018, Qinghai in 2017 and Shaanxi in 2018) as well. In respect of the provinces involved in the previous high-risk southern cluster, no CSF reports were noted in Guangxi after 2016, and CSF only re-occurred in Guizhou in 2018 after 2 years of zero CSF reporting. In contrast, the endemic status of CSF in Yunnan did not change. CSF outbreaks were continuously reported in Yunnan and the post-2012 annual counts were not too divergent from the pre-2012 counts.

3.2 | Relationships between climate variables and CSF reports

The results of cross correlation function analysis indicated that humidity and wind speed are the major factors correlated with CSF reports (Table 3). As correlation with an absolute value greater than $2/\sqrt{n-|k|}$ (n is the number of observations and k is the lag) is considered significant, the results suggested the following points:

1. For the population group II (Fujian, Gansu, Hainan, Jilin, Shaanxi, Shanxi and Zhejiang), the positive cross correlations between wind speed and CSF reports appeared to be significant from lag −12 to lag 0, which indicated that higher wind speed up to 12 months previously might lead to a higher occurrence of CSF outbreaks.
2. For the population group III (Anhui, Chongqing, Guizhou, Heilongjiang, Jiangsu and Jiangxi), the occurrence of CSF outbreaks was likely facilitated by low relative humidity.
3. If we disregard the potential effect of pig population size and potentially density, the CSF reports in the climate group C (Henan, Shandong, Jiangsu, Anhui, Hubei, Chongqing, Guizhou, Guangxi, Guangdong, Yunnan, Shanghai, Zhejiang, Jiangxi, Hunan and Fujian) were significantly affected by both wind speed and humidity. The results suggested that high wind speed one to seven months previously, and low relative humidity four to six months previously, may lead to more CSF outbreak reports.
4. For the climate group D, low humidity 4 months previously was significantly associated with higher numbers of CSF reports.

4 | DISCUSSION

By 2018, CSF outbreaks have been reported less frequently in mainland China. In most of the provinces, the annual count of CSF outbreak reports had been either significantly decreased or reduced to zero for at least 2 years. During the study period the general pattern of CSF outbreak distribution appeared to be sporadic, with a few exceptions identified by the current study: (1) CSF remained endemic in Yunnan, whilst the status of other provinces (Guizhou, Guangdong and Guangxi) in the southern China cluster during the 2000s improved greatly and (2) in Gansu, CSF was still endemic from 2012 to 2016, and the disease re-emerged in 2018 after 1 year of absence. In the case of latter, CSF outbreaks were consistently reported in adjacent provinces, possibly related to disease transmission from Gansu. CSF prevention and control measures in Gansu and the adjoining provinces (e.g. Qinghai and Ningxia) might be have been incorrectly applied, or applied without sufficient thoroughness. By analyzing the annual CSF report data from the OIE-WAHIS database, we also identified that less humidity (drier air) could increase the risk of CSF outbreaks 3–6 months later, and high wind speed was positively correlated with CSF outbreaks during an even longer time interval, up to 12 months.

As stated above, the epidemiological status of CSF in China has significantly improved during 2005–2018, but the outcome did not meet the national goal (Ministry of Agriculture and Rural Affairs, 2006; The State Council of the People's Republic of China, 2012). Although the final goal of CSF control has always been the regional and then national eradication of the disease, the minimum criteria for declaring 'incompletely immunized eradication region' are defined by the national CSF prevention and control protocol: (1) CSF case reports should be regularly and promptly submitted and assessed, (2) no CSF cases detected in the previous two years, (3) in the previous 12 months, no vaccination was performed and no vaccinated pigs were imported into the region after the vaccination ceased and (4) the region should be equipped with competent surveillance system and regionalization and no pathogen was detected in the previous two years (Ministry of Agriculture and Rural Affairs, 2006). For the 'completely immunized eradication region', the vaccination coverage within the region and adjacent buffer zones should reach 100%, and CSF cases should not have been diagnosed in the previous 3 years (Ministry of Agriculture and Rural Affairs, 2006). Since our data represented the annual count of CSF outbreaks in provinces and we lacked information on the exact case number, pathogenic and serological reports and the descriptive statistics on CSF vaccination, we cannot conclude that eradication was achieved in any region during the study period (2005–2018), despite CSF outbreaks having not been reported since 2012 in many provinces (including Guangdong, one of the provinces with the highest risk of CSF occurrence before 2012 and also the largest pig population). However, as the current study confirmed the reduction of CSF outbreak reports — consistent with previous reviews (Luo et al., 2014; Zhou, 2019), the effectiveness of the new animal disease control plan, and the development in the field of veterinary science and animal health management measures derived from it — the concept of ongoing eradication is well supported (The State Council of the People's Republic of China, 2012).

TABLE 3 The spatiotemporal cross correlations (*r*) between weather factors (wind speed and relative humidity) and classical swine fever (CSF) reports in China from 2005 to 2018. Significant correlations (absolute value $> 2/\sqrt{n - |k|}$; *n* is the number of observations and *k* is the lag) are shown by the shaded cells. Lag is the time interval (months) between the time-series of CSF reports and the environmental factors measured in months previously. Population group III are provinces with mean pig population size greater than or equal to the median and less than the upper quartile ($13,490 \leq n < 20,608$ thousand): Anhui, Chongqing, Guizhou, Heilongjiang, Jiangsu and Jiangxi. Climate group C are provinces with a temperate climate (Henan, Shandong, Jiangsu, Anhui, Hubei, Chongqing, Guizhou, Guangxi, Guangdong, Yunnan, Shanghai, Zhejiang, Jiangxi, Hunan and Fujian) and climate group D are provinces with a continental climate (Heilongjiang and Jilin)

	Wind speed				Relative humidity					
	Population group II		Climate group C		Population group III		Climate group C		Climate group D	
Lag	*r*	SE	*r*	SE	*r*	SE	*r*	SE	*r*	SE
−12	0.263	0.080	0.175	0.080	−0.087	0.080	−0.089	0.080	−0.041	0.080
−11	0.243	0.080	0.149	0.080	−0.074	0.080	−0.098	0.080	−0.060	0.080
−10	0.202	0.080	0.131	0.080	−0.069	0.080	−0.113	0.080	−0.136	0.080
−9	0.178	0.079	0.152	0.079	−0.056	0.079	−0.128	0.079	−0.105	0.079
−8	0.184	0.079	0.158	0.079	−0.077	0.079	−0.139	0.079	−0.119	0.079
−7	0.200	0.079	0.179	0.079	−0.121	0.079	−0.153	0.079	−0.039	0.079
−6	0.243	0.079	0.230	0.079	−0.170	0.079	−0.174	0.079	−0.070	0.079
−5	0.271	0.078	0.248	0.078	−0.196	0.078	−0.191	0.078	−0.146	0.078
−4	0.270	0.078	0.252	0.078	−0.184	0.078	−0.170	0.078	−0.185	0.078
−3	0.238	0.078	0.231	0.078	−0.185	0.078	−0.147	0.078	−0.155	0.078
−2	0.217	0.078	0.208	0.078	−0.106	0.078	−0.114	0.078	−0.081	0.078
−1	0.257	0.077	0.242	0.077	−0.120	0.077	−0.120	0.077	−0.128	0.077
0	0.276	0.077	0.213	0.077	−0.151	0.077	−0.155	0.077	−0.074	0.077

In contrast to progressive elimination, a low frequency of CSF epidemics was also reported randomly in several Chinese provinces (e.g. Anhui, Henan, Hubei, Hunan and Jilin) after 2012. In addition, CSF appeared to be persistently endemic in Yunnan and Gansu. This status demonstrates some potential defects in CSF prevention and control.

1. *The immunization failure concerns of the current vaccine and compulsory vaccination plan and management issues associated with small- or medium-scale farms*: As indicated by the national policy of compulsory immunization, CSF is one of the five Class I animal diseases in China, and theoretically every farmed pig should be vaccinated against CSF with two doses of vaccine approved by the Veterinary Bureau (Ministry of Agriculture and Rural Affairs, 2006; The State Council of the People's Republic of China, 2012). According to the national Animal Epidemic Prevention Law (The State Council of the People's Republic of China, 2021), any units or individuals that participate in animal husbandry can face legal liability if they fail to achieve the immunization goals. The major problem associated with the vaccination plan is not that farmers are not adequately vaccinating to their pigs [although the vaccination plans followed and performed by farmers are anecdotally suspected to lack standardization and be highly variable (Ministry of Agriculture and Rural Affairs, 2006)], but the effectiveness of the current vaccine. In China, the live C-strain vaccine was first developed in 1954 and it has been commonly used ever since (Qiu et al., 2006). The C-strain vaccine is highly efficacious against the predominant viral CSFV strains and safe to administer under most circumstances (Luo et al., 2014; Qiu et al., 2006; Zhou, 2019), but immunization failure in the vaccinated population can still be seen due to other factors, for example, co-infection with other immunosuppressive viruses such as PRRSV, which has been frequently observed in Chinese pig farms (Chen et al., 2019; Chen et al., 2015), defective vaccination schedule that did not follow the decline in maternal antibody and a lack of serology monitoring of piglets (Zhou, 2019). Moreover, the Chinese vaccination-based immunization strategy has also encountered problems including: farmers' suspicion regarding the quality of the free vaccine provided by the government [it was anecdotally noted that farmers tended to buy other commercial brands of CSF vaccine with uncertain efficacy and excessive pricing instead (Luo et al., 2014)]; and the lack of post-vaccination monitoring (Zhou, 2019). Recently, Chinese researchers have sought solutions to the non-ideal immunization outcomes of the C-strain vaccine by developing new marker vaccines against CSFV (Gao et al., 2018; Xia et al., 2016), as well as discussing the potential effects of other preventive measures previously overlooked by Chinese farmers, for example, farm biosecurity and other farm environmental control strategies (Zhou, 2019).

2. *Variation in regional supervision and technical support levels*: All of the issues listed above are more of a concern in small- and medium-scale pig farms (yearly production < 500 pigs slaughtered), which accounts for over 90% of the pig farms in China (Liu et al., 2021; Riedel et al., 2012). Pork producers owning small- or medium-scale herds often lack systematic education on animal disease prevention and control measures, have limited funds and may suffer from insufficient rural veterinary technological support, facilities and services (Luo et al., 2014).

It is noteworthy that the main purpose of the national policy and protocol for CSF control is to provide an overall direction for provincial, city, and county decisions (The State Council of the People's Republic of China, 2012), and that standardized, replicable methods were not formulated in China due to huge regional disparities. This has resulted in the highly community-based and variable animal epidemic prevention and control measures in regional China. The local officers from government departments at the township or lower levels self-adapt and conduct district-specific prevention and control plans under the supervision of the county-level authorities. Besides that, the animal health surveillance, monitoring and control systems are relatively independent between provinces, as inter-provincial cooperation is uncommon and only triggered by major animal epidemics. Gansu is one such example. It is one of the provinces constantly affected by inadequately controlled CSF outbreaks and is one of the most economically underdeveloped provinces (Bureau of Statistics of the People's Republic of China, 2018) [e.g. in 2017 the gross domestic product (GDP) was 7677 billion Yuan with a GDP growth rate of 3.6%, while its neighbouring province Shaanxi had an annual GDP of 21,899 billion Yuan and a growth rate of 8%] (Bureau of Statistics of the People's Republic of China, 2018). During the study period (2005–2018), CSF outbreak reports were significantly fewer in Shaanxi compared to the adjacent provinces (including Gansu) in 2005, 2007, 2008 and 2012 despite the provincial pig population sizes and climate conditions being similar in the two provinces (Ministry of Agriculture and Rural Affairs, 2020). Limited investment capability as well as lack of professional support within an overall underdeveloped economy might be one of the major factors inhibiting the successful conduct of the CSF control plan.

Yunnan province borders CSF endemic, tropical southeast Asian countries (Choe et al., 2020). Prior to the incursion of ASF and related updates on pig production protocol and policy in 2019 (The Provincial Council of the People's Government of Yunnan Province, 2019; The State Council of the People's Republic of China, 2019), pig production in Yunnan was characterized by a small-scale, backyard system (Riedel et al., 2012). In the mountainous, rural areas of Yunnan, farmers commonly kept 2–5 pigs in their backyard and fed them with both materials collected or cultivated locally and commercial feed (Riedel et al., 2012). This production system is characterized by poor performance and high mortality due to lack of inputs and veterinary supervision, as well as improper husbandry approaches. There was also a preference for selling pork at local markets, so the occurrence of infectious diseases such as CSF could be masked, therefore creating a barrier to disease eradication. In recent years, two major changes have taken place: (1) large-scale pig producers have been relocating to Yunnan to reduce pollution in coastal areas (e.g. Guangdong) (Ministry of Agriculture and Rural Affairs, 2016) and (2) in 2019, the provincial government also published their opinions regarding national ASF control strategies. These changes enhanced both financial and technological support to small- and medium-scale pig producers (The Provincial Council of the People's Government of Yunnan Province, 2019; The State Council of the People's Republic of China, 2019), brought stricter border animal quarantine and inter-provincial animal examination and tracking standards and implemented more frequent serological and pathogenic monitoring in Yunnan. A further reduction in provincial CSF outbreaks could be expected to happen in the near future.

3. *Issues with wild boar CSF management*: Wild boar are an important vector and wild reservoir of CSFV (Moennig, 2015). It has been shown that CSF is endemic in the wild boar populations in Europe, and spillover events led to epidemics of CSF in farmed pig populations (Fritzemeier et al., 2000; Kaden et al., 2008; Moennig, 2015). From 2001, oral vaccination in the form of baits has been distributed in European countries to minimize CSF infection within wild boar populations (Council of the European Union, 2001; Kaden et al., 2008, 2010, 2001; von Rüden et al., 2008). Similarly, the risk of transmission of ASF via direct contact between wild boar and domestic pigs was important (Guinat et al., 2016). The importance of monitoring and managing infectious diseases in wild boar has also been recognized by Chinese researchers (Luo et al., 2014; Zhou, 2019), but national protocol on the measures against either CSF or ASF in wild porcine populations is currently absent in China (Ministry of Agriculture and Rural Affairs, 2006; The Provincial Council of the People's Government of Yunnan Province, 2019; The State Council of the People's Republic of China, 2012, 2019). It may be attributed to wild animals in China being under the management of the National Forestry and Grassland Administration (National Forestry and Grassland Administration, 2000), and disease prevention or control activities in wild boar populations require cross-sectoral cooperation in the government. To achieve the vaccination-based national CSF and ASF eradication plans and prevent future re-emergence of these diseases, wild boar in China should be managed more closely and the use of bait vaccination might be a cost-efficient method to be applied nationwide.

4. *Other factors—Strain virulence and climate*: In China, CSF subgenotypic strains are diverse (Zhou, 2019). The strains are different in their virulence, which can result in variation in transmission patterns (e.g. low-virulence strains may cause chronic, asymptomatic infection and life-long shedding of CSFV if not culled immediately) (Weesendorp et al., 2009; Weesendorp et al., 2014). Therefore, the potential source and route of entry of CSFV present in China should be explained by prospective national monitoring of the CSFV strains.

We found an association between CSF reports and low relative humidity in the previous three to six months. Although the underlying mechanism remains unclear, it is known that low relative humidity prolongs the survival of enveloped viruses (e.g. influenza virus and poxvirus) in the environment (Yang & Marr, 2012). As CSFV is an enveloped virus (MacLachlan & Dubovi, 2016), our results support effects of relative humidity on virus survival and the subsequent transmission of this enveloped virus (Yang & Marr, 2012). However, the association between relative humidity and the survival of CSFV has been rarely investigated in previous research. Additional observational and laboratory studies should be performed in the future to confirm this correlation.

Intriguingly, we found that high wind speed significantly promoted the future occurrence of CSF between 1 and 12 months later. According to previous knowledge, higher wind speed is associated with wider dispersion of aerosolized pathogens and higher risk of infection (Courault et al., 2017; Machado et al., 2019). We speculate that the significant positive correlation between wind speed and the occurrence of CSF indicates that airborne transmission of CSFV contributes to CSF outbreaks in China. However, it has also been suggested, based on a pen trial using CSFV and inoculated pigs, that higher air speed slightly reduces the half-life of virus aerosols (Weesendorp et al., 2008). It was speculated that higher air speed could cause mechanical stress to the virus. There are likely at least two different mechanisms operating with respect to wind speed. One is a potential negative effect on virus survival (slightly shorter half-life as air speed increases), and the second is likely widespread dispersion of infectious virus aerosols. Our analysis is hypothesis-generating and indicates that the role of ariborne spread of CSFV needs more investigation. As air speed management could be a crucial factor to reduce the risk of viral infection (Courault et al., 2017; Otake et al., 2002), further investigations on the nature of CSFV aerosols in Chinese pig farms may have practical importance.

It should also be acknowledged that the current study possessed several limitations:

1. The retrospective data we used were accessed from the OIE-WAHIS database, which is not primarily designed for observational research studies and therefore lacked detailed information that might affect the analyses (Sørensen et al., 1996), for example, the detailed geographical coordinates of each reported outbreak, the vaccination and transport history of the affected farms, the on-farm husbandry measures, the sub-genotypes of CSFV and the demography of the infected pigs, or pigs suspected to be infected.
2. The unavoidable but non-differential reporting bias. In the current study, we did not have definite evidence to dismiss the possibility of underreporting of CSF in China. Potentially, underreporting could be caused by misdiagnosis and farmers' concealment due to either lack of knowledge or dissatisfaction about the financial compensation offered by the authorities for culling (Luo et al., 2014). In China, the definite diagnosis of CSF also requires the support of clinical signs and pathological changes, epidemiological investigations, immunological tests, for example, enzyme-linked immunosorbent assay (ELISA), molecular tests, for example, reverse transcription polymerase chain reaction (RT-PCR) and isolation of the CSFV (Zhou, 2019). Despite the defined diagnostic criteria of CSF, diagnostic assays including RT-PCR and ELISA were not commonly used in regions without sufficient veterinary resources in China during our study period (Luo et al., 2014; Ministry of Agriculture and Rural Affairs, 2006; Zhou, 2019). The diagnosis heavily relied on the variable and atypical clinical signs, and therefore it likely led to underdiagnosis (Moennig & Becher, 2015; Schulz et al., 2017; Zhou, 2019). As laboratory testing has been progressing for years and has become more popular, and recently commercial diagnostic kits for CSF became available in China (Zhou, 2019), the diagnosis efficacy of CSF is improving. However, even if the underreporting was present, it is unlikely that it caused a major impact on the current study. CSF, as a Class I animal infectious disease, is strictly managed by the government and the level of underreporting is likely minimal compared to other diseases posing less threat to the industry [e.g. colibacillosis, which is a Class III animal infectious disease (The State Council of the People's Republic of China, 2021)]. We also assumed that the degree of underreporting was equal across provinces and the data were only used for comparative purposes. Therefore, the results of the correlation analyses performed are not expected to be biased.

5 | CONCLUSIONS

The current study confirmed the improved situation of CSF control in China, with outbreaks becoming sporadic and gradually decreasing in number. However, the results indicated that CSF was still endemic in at least two provinces (Yunnan and Gansu). Therefore, effective, updated and standardized CSF prevention and control measures are urgently required in China.

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ETHICS STATEMENT

Informed consent for collection of epidemiological data was not required, as these data were already available in the public domain. No identifiable personal information was used in this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Michael P. Ward https://orcid.org/0000-0002-9921-4986

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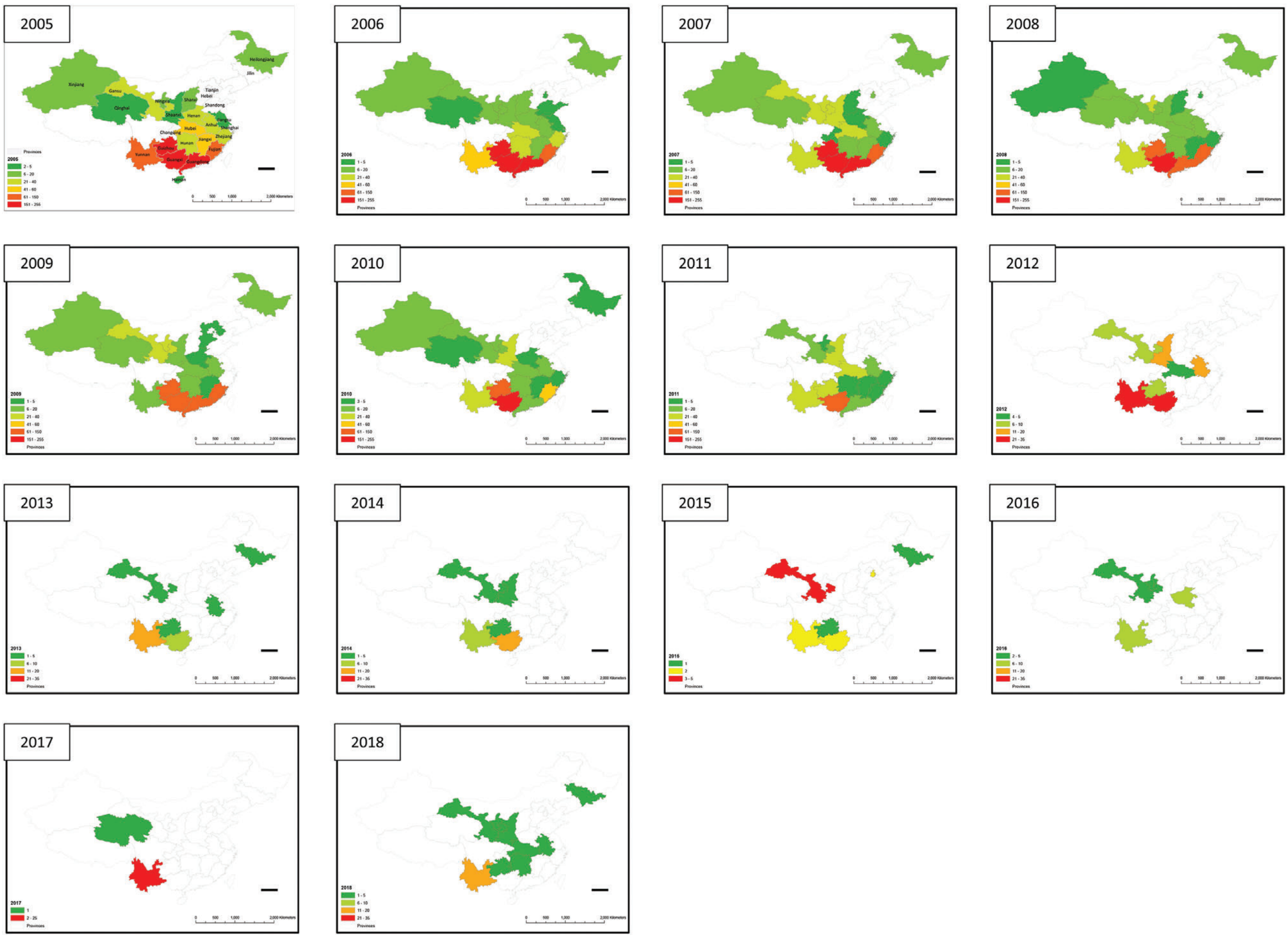
APPENDIX I

Annual choropleth maps of reports of classical swine fever, China, 2005–2018



APPENDIX II

Spatial clusters (high–high and low–low) and outliers (high–low and low–high) of annual counts of classical swine fever (CSF) reports per Chinese province, 2005–2018. The year 2017 was excluded since CSF outbreaks were only reported in two provinces