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Spatiotemporal Pattern of Pine Wilt Disease in the Yangtze River Basin

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Abstract: The Yangtze River Basin is among the river basins with the strongest strategic support and developmental power in China. As an invasive species, the pinewood nematode (PWN) *Bursaphelenchus xylophilus* has introduced a serious obstacle to the high-quality development of the economic and ecological synchronization of the Yangtze River Basin. This study analyses the occurrence and spread of pine wilt disease (PWD) with the aim of effectively managing and controlling the spread of PWD in the Yangtze River Basin. In this study, statistical data of PWD-affected areas in the Yangtze River Basin are used to analyse the occurrence and spread of PWD in the study area using spatiotemporal visualization analysis and spatiotemporal scanning statistics technology. From 2000 to 2018, PWD in the study area showed an "increasing-decreasing-increasing" trend, and PWD increased explosively in 2018. The spatial spread of PWD showed a "jumping propagation-multi-point outbreak-point to surface spread" pattern, moving west along the river. Important clusters were concentrated in the Jiangsu-Zhejiang area from 2000 to 2015, forming a cluster including Jiangsu and Zhejiang. Then, from 2015–2018, important clusters were concentrated in Chongqing. According to the spatiotemporal scanning results, PWD showed high aggregation in the four regions of Zhejiang, Chongqing, Hubei, and Jiangxi from 2000 to 2018. In the future, management systems for the prevention and treatment of PWD, including ecological restoration programs, will require more attention.

Keywords: Yangtze River Basin; pine wilt disease; spatiotemporal scanning; spatiotemporal cluster; county scale

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1. Introduction

The Yangtze River Basin is among the river basins with the strongest strategic support and development power in China. It has played an irreplaceable role in the processes of China's provincial economic transformation and industrial structure optimization. The Yangtze River Basin consists of three national-level urban agglomerations (the Yangtze River Delta, the Middle Reaches of the Yangtze River, and the Chengdu-Chongqing urban agglomeration). The Yangtze River Basin is among the regions with the strongest overall strengths and strategic positions in China [1]. With the development of international trade and tourism, biological invasion is becoming an important threat to China's biodiversity and ecological environment [2]. Over the past 30 years, the population and economy in this region have rapidly grown at the cost of the local ecosystems, resulting in environmental degradation, and the degradation of the terrestrial ecosystem in the upper reaches of the Yangtze River and the aquatic ecosystems in the middle and lower reaches of the Yangtze River continue [3]. In the Yangtze River Basin, new ecological and environmental problems, such as declining biodiversity and the fragmentation of habitats, have become increasingly prominent, and the ecological–environmental security situation is not optimistic.

Pine wilt disease (PWD) is a worldwide forest disease caused by the pinewood nematode (PWN) *Bursaphelenchus xylophilus* [4]. This disease causes the devastating death of pine trees by affecting the water transport function of the trees [5]. A global conifer disease, PWD is one of the most serious threats to pine trees in Asia and Europe [6]. The disease spreads with globalization [7], and climate change further promotes its spread [8]. The PWN originated in North America and was introduced to Asia through the Japanese wood trade. PWD first appeared in Kyushu, Japan, in the early 20th century, spread to surrounding areas in the 1930s [9] and then swept across Japan. In 1982, China first discovered the PWN on black pine trees in Zhongshan Mausoleum in Nanjing, and 256 dead trees were found [10]. PWD occurred not only in Nanjing city and the suburban counties but also spread rapidly at a rate of 7000–10,000 hm^2 per year, extending to surrounding counties and cities [11]. In just a few decades, the disasters spread from Nanjing to Jiangsu, Zhejiang, Anhui, and other places. PWD in Chongqing was first discovered in 2011 at the junction of Fuling and Changshou [12]. PWD first appeared in Jiangxi in 2003 in Zhanggong District, Ganzhou city. By 2014, a total of 99 counties in Jiangxi were threatened by PWD. As of the end of 2019, PWD had been identified in all 10 provinces and cities outside of Shanghai in the Yangtze River Basin (The National Forestry and Grassland Administration, 2020). By applying the MaxEnt model to predict the area suitable for pinewood nematodes in China, the suitability level of the disease in the Yangtze River Basin was found to be relatively high, and a high risk of infection was identified in this region [13]. Under future climate change, the suitable areas for the PWN are expanding [8].

Invasive alien species are highly dangerous and pose serious threats to the sustainable development of forest ecosystems [14]. As one of these invasive species, the PWN has introduced a serious obstacle to the high-quality development of the economic and ecological synchronization of the Yangtze River Basin. The characteristics of PWD caused by the PWN include multi-channel transmission, partial concealment, a rapid onset, a long incubation time, and difficult management. Since PWD first appeared in Nanjing in 1982 [10], it has appeared and is now epidemic in parts of the Yangtze River Basin, such as Anhui and Zhejiang, causing massive losses to China's abundant pine resources. As a greening tree species, pine is the main tree species used for forested ecological barriers such as barren mountain afforestation and coastal protection forests in the Yangtze River Basin. The red and yellow soil areas of the Yangtze River Basin are facing serious soil erosion and poor soil conditions [15]. PWD damages the forest coverage, forest quality, and land productivity; these factors are difficult to restore, and their destruction easily leads to soil erosion and causes mudslides, mountain torrents, and many ecological disasters [16]. PWD epidemics have been found in important ecological locations, such as the Three Gorges Reservoir area, Qinba Mountain, Zhangjiajie, Lushan, Qiandao Lake, and many key national scenic spots [17]. PWD has caused serious damage to the natural landscape, ecological environment, and social economy in China.

The forest resource losses caused by the PWN have received widespread concern and a great amount of attention. Extensive research and technology have been invested in the prevention and control of PWD. PWD is the result of a combination of multiple pathogens, host pine trees, insect vectors, and climatic conditions [18]. In 1971, it was confirmed that the pathogen causing PWD was the PWN [19], and the incidence cycle of PWD was determined through detailed research [10]. Research has pointed out that temperature is very important for the PWN, and the average temperature of their environment is above 20 °C [20]. The effective cumulative temperature of the species particularly ranges within 25–30 °C, and an increase in the PWN population promotes the growth of the population of trees experiencing PWD [21]. The research results of Matsuhashi and others have indicated the effect of temperature on the spread of PWD in Japan [22]. Morimoto proposed that the spread of PWD was achieved by the transmission of the pinewood nematode through several species of Monochamus alternatus [19]. As the transmission medium of the PWN, the spreading ability of these Monochamus alternatus species are an important sign of the spread of PWD in nature [23]. This distribution plays a major role in the formation of the local infection centre, and the spread of the local infection centre itself also involves the coordination of other natural diffusion pathways [24]. Robinet pointed out that world trade expanded the distribution of the pathogenic species through long-distance transmission during the spread of PWD [25]. Choi, Won Il, et al. showed that PWD was mainly spread by jumping diffusion in the early reinvasion stage [26]. Human activities directly affect the scale of the spreading of PWD. Takasar Hussai et al. used a mathematical model to analyse dynamic changes in the transmission of PWD [27]. To explore the most important factors affecting the spread of PWD, Muhammad Ozair conducted a sensitivity analysis of the influential parameters [28]. These studies all contributed to the analyses and risk assessment models of PWD.

To date, PWD research in the Yangtze River Basin in China has adopted relatively coarse resolutions, and few studies have been conducted at the county scale. At present, many studies have examined the spread of PWD by analysing the biological characteristics, such as the pathogenesis and fitness characteristics, of the PWN. The scope of past research was small, the duration was short, the results were fragmented, and the outputs lack any macroscopic long-term evolutionary trends. The rapid spread of PWD has seriously affected the safety of the ecological environment of the forests in this area. With the continuous development of the economy and trade, the prevention and control of pests and diseases in the Yangtze River Basin urgently needs to be addressed. In this study, 11 provinces and cities in the Yangtze River Basin were used as research areas to analyse the occurrence and spread of PWD in the Yangtze River Basin with the aim of effectively managing and controlling the spread of the disease.

2. Materials and Methods

2.1. Study Area

The Yangtze River Basin is densely populated and economically developed. It spans the three major regions of eastern, central, and western China, covering 11 provinces and cities, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou, with a total area of approximately 2.0553 million square kilometres, accounting for 21.4% of China. The total population, regional GDP, and tertiary industry output value of the Yangtze River Basin exceed 40% of the national totals. This region has unique geographical advantages and vast development potential. The natural climate of the study area is complex and diverse, and the social factors have obvious differences among different regions. The soil types are diverse, and there are many rivers and lakes, abundant natural resources, and rich flora and fauna. The study area is located in the northern temperate zone with a humid climate, constituting the most suitable area for the growth of pine trees. Many types of pine trees are widely distributed in this region, with strong adaptability to the soil.

2.2. Data Collection and Pre-Processing

This study used statistical PWD area data obtained in China from 2000 to 2018. The county-level disaster area data of PWD were provided by the Forest and Grassland Pest Control Station of the State Forestry and Grassland Administration of China (www.forestpest.org, accessed on 6 July 2020). The statistical data on the occurrence of PWD areas were collected by the forestry bureaus of various districts and counties in China. The data were reported to the National Forestry and Grass Administration Forest and Grassland Pest Control Station of China through the autumn census and the Spring Festival census each year. The data fields include the occurrence area of PWD and the increase or decrease in area as well as the numbers of diseased and dead trees and the increase or decrease in the numbers of diseased and dead trees. The data were checked by the Quarantine Office of the Forest and Grassland Pest Control Station of the State Forestry and Grassland Administration.

Additionally, the normalized difference vegetation index (NDVI) data used in this study included China's monthly 1-kilometer NDVI spatial distribution data set, which is based on NDVI time-series data obtained from satellite-derived remote sensing images such as SPOT/VEGETATION and MODIS. These NDVI data were generated based on ten-day data using the maximum value synthesis method, that is, the maximum value in the NDVI data from three periods of ten days per month. The spatial extent of this data covers the whole country with a spatial resolution of 1 km. This data set effectively reflects the distribution and changes in vegetation coverage on spatial and temporal scales in various regions of the country.

While no data on the total PWD incidence were available in each county's host area or in the entire study area, NDVI and vegetation coverage have been shown to have a good positive correlation [29,30], and NDVI is highly sensitive to changes in vegetation coverage [31]. This study assumes that the standardized vegetation index in December approximates the vegetation coverage rate. The study area is located in southern China, and susceptible pinewood nematode hosts are widely distributed throughout this region. In the study area, during a cold winter in December, the vegetation was basically deciduous or withered, while the healthy pine coniferous forest was evergreen, showing the characteristics of green vegetation. The vegetation coverage rate in this period can be roughly regarded as the host vegetation coverage rate, which is the best available metric for extracting the distribution area of the pine coniferous forest. NDVI data were used to calculate the vegetation coverages in different county-level administrative regions. In this study, the host area was estimated using the product of the county area and the vegetation coverage. Then, the incidence of PWD was calculated based on the ratio of official statistical data records to the area of the host. Although this process cannot accurately calculate the exact value, it can reasonably represent the corresponding quantitative relationships and actual meanings of the variables among different geographic units.

The provincial-level disaster data used in the study were compiled from official county statistics, and the number of affected counties was considered to be equal to the statistical value of counties with non-zero disaster areas. In this study, the retrospective spatiotemporal scanning method was used, the PWD-infected area in the epidemic area was used as an independent variable, and the evolutionary trends of the spatiotemporal pattern of PWD infestation and spread from 2000 to 2018 were statistically analysed.

2.3. SaTScan Model

The SaTScan spatiotemporal scanning method uses spatial, temporal, or spatiotemporal scanning statistics to analyse spatial, temporal, and spatiotemporal data, respectively, and is widely used to detect and predict the clustering of widespread diseases [32]. In addition, this method has been applied in many fields, such as archaeology, astronomy, criminology, geology, geography, and ecology. This study uses the discrete Poisson model to study the distribution of PWD in the Yangtze River Basin of China. The area of pine trees was taken as the risk area, and the disaster area was taken as the event, with the years and county-level administrative districts set as the temporal and spatial scanning units. Based on the spatiotemporal characteristics of the distribution of PWD at the county level in China, the maximum scanning window of the Poisson spatial scanning model was set to 30%, and the first 5 aggregation areas were selected for the analysis of the spatiotemporal aggregation of PWD. In this study, the calculation was performed by the SaTScan$^{\mathrm{TM}}$ software 9.4.4 developed by Martin Kulldorff [33]. The formula used for the calculation was as follows:

$$LLR = \log\left(\frac{s}{E(s)}\right)^{s}\left(\frac{S-s}{S-E(s)}\right)^{s} I(), \tag{1}$$

where s is the actual disaster area in the scanning window, S is the total disaster area, $E(s)$ is the theoretical disaster area in the window corrected by covariates under the null hypothesis, and $I()$ is an exponential function. When the actual disaster area in the window is higher than the theoretical disaster area, $I() = 1$; otherwise, $I() = 0$.

This method creates a cylindrical window whose size, position and height dynamically change in the complete research area; the window scans and counts until the parameters reach the upper limit set by the scanning window. In the scanning process, the log-likelihood ratio (*LLR*) of the actual occurrence number and expected occurrence number inside and outside the scanning window is used as the scanning statistic. The *LLR* is used to scan and detect abnormal values in the window. The scanning window in which the maximum *LLR* value is obtained in the scanning results is called the class-I high-aggregation area, and the remaining statistically significant scanning windows are considered the class-II aggregation areas. For all scanning windows, H1 indicates that the spatiotemporal distribution of PWD is completely random, while H0 indicates that the area of PWD in the window is larger than the area outside the window. The data set generated on the null hypothesis is used to perform Monte Carlo hypothesis testing. Under the null hypothesis, if the *LLR* of the aggregation area exceeds 95%, it is considered significant at the 5% level (p-value = 0.05), indicating that the PWD disease area in the scanning window is abnormal. The PWD incidence is large and concentrated in the affected area, manifesting as a clustered outbreak.

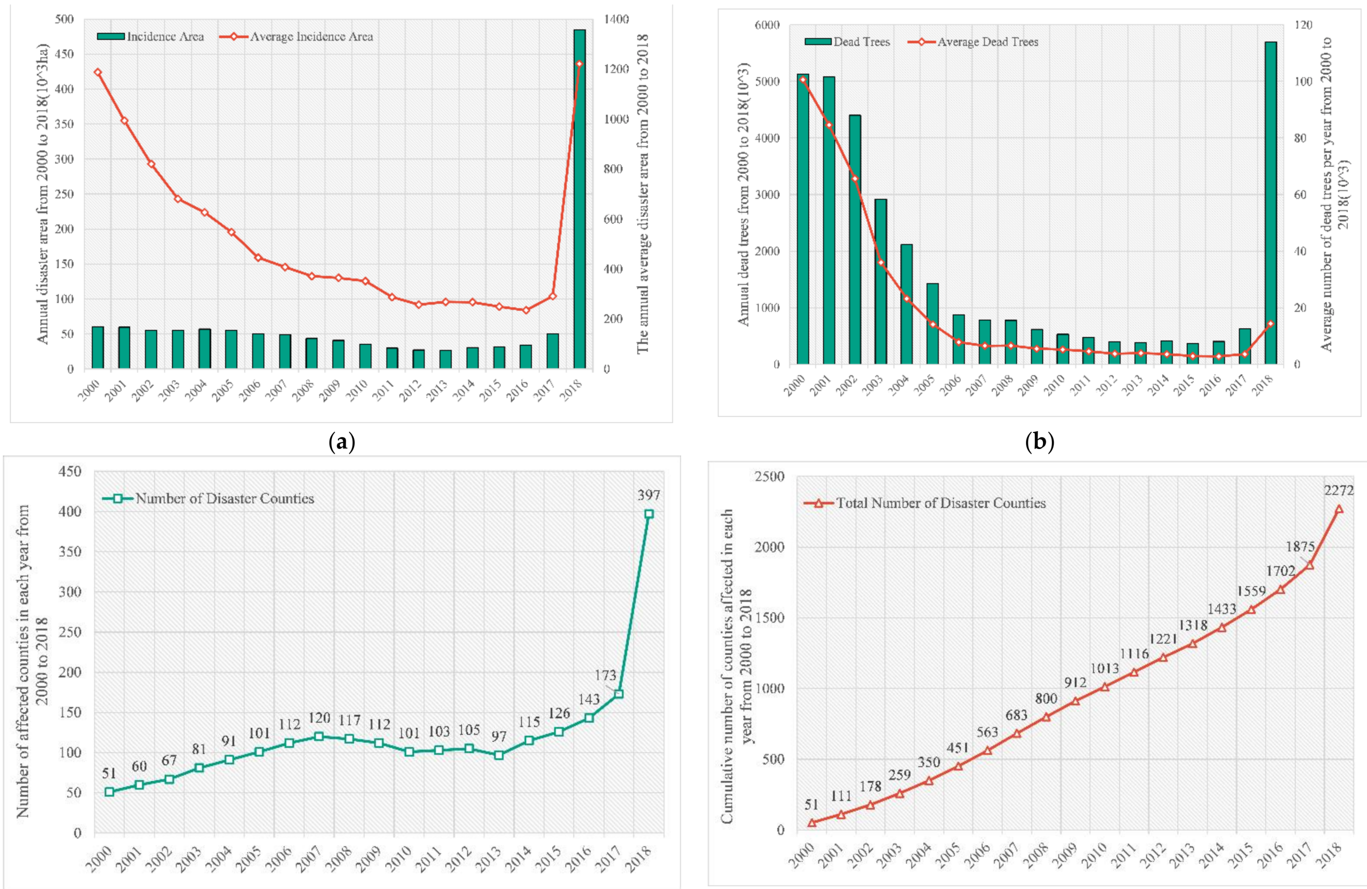
3. Results

3.1. The Overall Change Trend

From 2000 to 2018, the overall disaster trend of PWD in the 11 provinces of the Yangtze River Basin showed an "increasing-decreasing-increasing" trend, and PWD increased explosively in 2018. These disaster characteristics of PWD were reflected in the changes in the disaster area and the number of dead trees over the 19 studied years (Figure 1).

The area affected by the PWN showed a trend of first declining and then rising. According to these transmission characteristics, the evolution of the disaster-affected area in the Yangtze River Basin region over the past 18 years could be divided into two stages (Figure 1a): (1) the slow decline stage from 2000 to 2013 and (2) the rapid expansion stage from 2013 to 2018. In the first stage, the area of PWD infestation was largest in 2000, reaching 60,578 hectares. After 2000, the area affected by PWD in the Yangtze River Basin slowly decreased annually and dropped to the lowest value in 2013, with an average annual decrease of 2655 hectares. After 2013, the changing trend of the PWD area entered the second stage, and the PWD area began to grow rapidly. Among these increases, the average annual growth rate from 2013 to 2017 was 6078 hectares, which was 2.3 times the growth rate measured in the first stage. In just one year, in 2018, the infested area increased exponentially, reaching 484,614 hectares, which was 9.6 times that of the previous year, and the growth rate was 860%. Taking the average disaster area of the county as the research object, a slow decline was observed from 2000 to 2017. In 2018, the average disaster area of the county increased rapidly, reaching the same status as that recorded in 2000, at 1188 hectares per county and 1221 hectares per county, respectively. The average disaster area in the county reached its lowest level in 19 years in 2016, at 235 hectares per county.

The changing trend of PWD-affected dead trees can be divided into three stages (Figure 1b): (1) the reduction stage from 2000–2013, (2) the stable stage from 2014–2016, and (3) the outbreak stage from 2017–2018. The most dead trees were observed in the Yangtze River Basin in 2000 and 2001, with 5,132,053 trees and 5,075,845 trees, respectively. In the first stage, the rate of decline of dead trees from 2001 to 2006 was rapid, reaching an average of 839,024 trees per year. From 2006 to 2013, the number of dead trees continued to decrease, but the rate of decrease declined annually. In the second stage, the number of dead trees was relatively stable and was maintained at approximately 400,000. From 2017 to 2018, the number of dead trees increased rapidly and reached 5,693,995 in 2018. The annual average number of PWD-affected dead trees in the Yangtze River Basin was basically consistent with the three stages of dead tree observations. From 2001 to 2013, the annual average number of dead trees decreased annually, during which time the rate of decrease was highest during 2000–2006; the annual average numbers of dead trees were relatively constant during 2014–2016. The average annual increase in the number of dead trees from 2017 to 2018 was lower in magnitude than the rate of decrease in the period from 2000 to 2006.



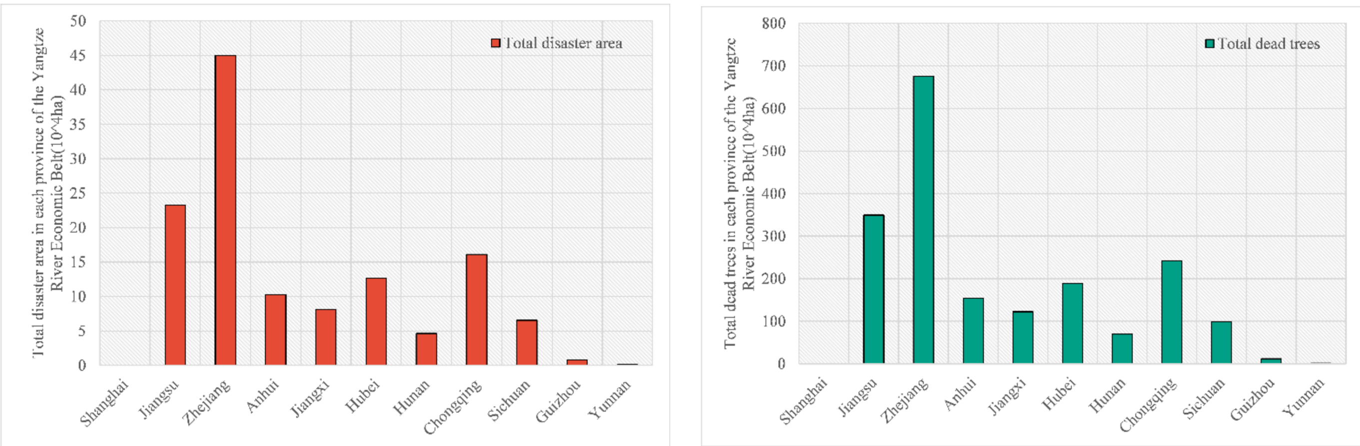
(a) (b) (c) (d)

Figure 1. Disaster situation of pinewood nematodes in the Yangtze River Basin from 2000 to 2018: (**a**) disaster area and average disaster area of the affected area; (**b**) diseased and dead trees in the affected area and the mean number of dead trees; (**c**) the number of affected counties in the Yangtze Basin; (**d**) the cumulative number of affected counties in the Yangtze Basin.

The change in the number of affected counties as a whole represented a "growth-steady-outbreak" development pattern (Figure 1c,d). The changes in the infested area and the average annual disaster area, the number of dead trees, and the average annual number of dead trees were not completely consistent, so the PWD infestation rate was closely related to the number of affected counties (Figure 1a,b). From 2000 to 2007, the number of affected counties increased slowly, from 51 to 120; during the period from 2008 to 2013, the number of affected counties remained relatively stable and decreased to a certain extent. From 2014 to 2018, the number of affected counties began to increase; the number increased to 173 in 2017, then rapidly increased to 397 in 2018. The cumulative number of counties affected by PWD increased at a uniform rate, with an average annual growth rate of 107 from 2000 to 2017 and a rapid growth rate of 397 per year from 2017 to 2018.

3.2. The Provincial-Level Spatiotemporal Diffusion Model

The older affected areas of Zhejiang Province and Jiangsu Province, located in the lower reaches of the Yangtze River, were more severely affected than the middle and upper reaches of the Yangtze River. Hubei, Chongqing, Jiangxi, and other areas were more seriously affected in the upper reaches, with severe epidemics. According to the statistical results of the cumulative disaster area and the number of dead trees in each province from 2000 to 2018 (Figure 2), the areas with the most severe effects in the past 19 years were the Zhejiang and Jiangsu povinces. The cumulative disaster areas and the numbers of dead trees were both at high levels in these provinces. Zhejiang Province ranked first in its disaster area and number of dead trees, with 450,165 hectares and 22,547,000 trees, respectively; these values were significantly higher than those of the other regions, and Zhejiang Province is the only region where the number of dead trees exceeded 10 million. Jiangsu Province ranked second in its disaster area and number of dead trees, with 232,813 hectares and 5,225,000 trees. In the upper and middle reaches of the Yangtze River, Chongqing municipality and the Hubei and Jiangxi provinces suffered serious epidemics. The disaster area in Chongqing reached 160,928 hectares, second only to Jiangsu Province in the Yangtze River Basin. Large numbers of dead trees were recorded in the Jiangxi and Hubei provinces, both exceeding 1,400,000. In the study area, the PWD epidemic situations in Shanghai, Guizhou, and Yunnan were relatively mild. In these regions, the disaster areas were smaller than 10,000 hectares, and the numbers of dead trees were under 20,000.



(**a**) (**b**)

Figure 2. PWD situations in all provinces of the Yangtze River Basin: (**a**) cumulative disaster areas in all provinces; (**b**) the number of dead trees accumulated in each province.

All provinces in the Yangtze River Basin were affected by PWD, and the overall situation in the lower reaches of the Yangtze River was more severe than elsewhere in the basin; however, this situation has been controlled to a certain extent. The spread of PWD in the middle and upper regions was not optimistic. PWD began to expand in 2013 and broke out in 2018 (Figure 3). The provinces of Zhejiang, Jiangsu, and Anhui in the lower reaches of the Yangtze River were the areas that were most severely affected by disasters for 19 consecutive years, from 2000 to 2018. The disaster area and the number of dead trees in Zhejiang Province first increased and then decreased, but the scope of the spread continued to increase. The number of infested counties in Jiangsu Province was relatively stable, and the disaster area and the number of dead trees were controlled in the later period. Before 2017, the spread of PWD in Anhui Province slowed, but an epidemic broke out in 2018, at which time the affected area, number of dead trees and affected counties all increased rapidly. The epidemic situation in the middle and upper reaches began to expand after 2013. PWD broke out in 2018 and showed a trend of continuous growth. In the upper and middle reaches of the Yangtze River, Sichuan, Hubei, Hunan, Chongqing, and Jiangxi provinces had relatively mild outbreaks in the early stage, but PWD gradually spread after 2013 and broke out completely in 2018. The number of affected counties in the Sichuan, Hunan, and Jiangxi provinces increased rapidly after 2013. This epidemic was reflected in the affected areas and numbers of dead trees in 2015 and 2016. Both Chongqing municipality and Hubei Province grew rapidly during 2016–2018. Among the 11 provinces and municipalities, PWD was controlled in both Shanghai and Yunnan and disappeared after the outbreak.

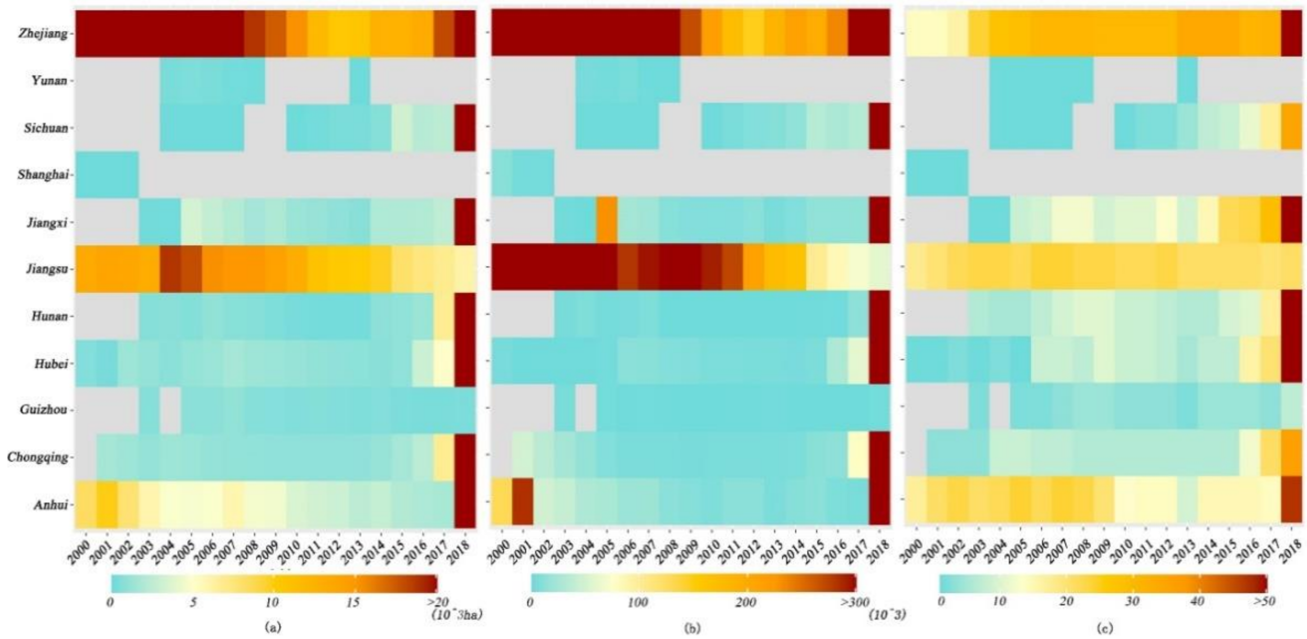


Figure 3. The time series changes of the provinces of the Yangtze River Basin from 2000 to 2018: (**a**) trends of the infested area in each province; (**b**) trends in the number of dead trees in each province; (**c**) trends in the number of affected counties in each province. (The horizontal axis represents the time, the vertical axis represents the name of the region, and the colours represent the disaster area, the number of dead trees and the number of affected counties in that year; thus, the changes of the PWD epidemic situation in each province can be seen intuitively).

3.3. County-Scale Diffusion of PWD

The spread of regional disasters in the Yangtze River Basin showed a "jumping propagation-multi-point outbreak-point to surface spread" pattern throughout the whole diffusion period (Figures 4 and 5). PWD spread along the western region of the Yangtze River, and the Chongqing disaster area comprised the disaster area in the lower reaches of the Yangtze River. The lower reaches of the Yangtze River were still the most severe PWD areas, forming a "high-high" cluster area.

From 2000 to 2010, PWD spread along the Yangtze River to inland areas in a leaping manner, and the disaster in Chongqing was the most severe. In 2005, several newly affected counties appeared in Chongqing. The number of dead trees was under 5000, and the incidence rate in the most severe districts and counties exceeded 5%. In 2010, the number of newly infested counties in Chongqing, Hubei, Hunan, and Jiangxi increased. In addition, over the last decade, PWD gradually moved south to the coastal areas of Zhejiang. In 2015, the epidemic showed a trend of multiple outbreaks in the Yangtze River Basin, and PWD continued to spread. Many infested counties were recorded in Chongqing, Hunan, and Jiangxi, with incidence rates mainly ranging from 0–0.5%. The number of dead trees was within 5000, and the numbers of dead trees in a few districts and counties in Chongqing were between 5000 and 1000. By 2018, PWD had continued to spread, a large number of newly infested counties appeared, and the affected counties were continuously distributed.

PWD covered Zhejiang Province and central and southern Jiangsu Province. In the middle and upper reaches of the Yangtze River, Chongqing was the most seriously affected area, with incidence rates exceeding 10% in many counties and districts. Chongqing was almost completely covered by PWD, replacing the cluster in the lower reaches of the Yangtze River as the most seriously infested area in the study area. Additionally, the Hubei, Hunan, and Jiangxi provinces had high disease incidences and numbers of dead trees, covering a wide range.

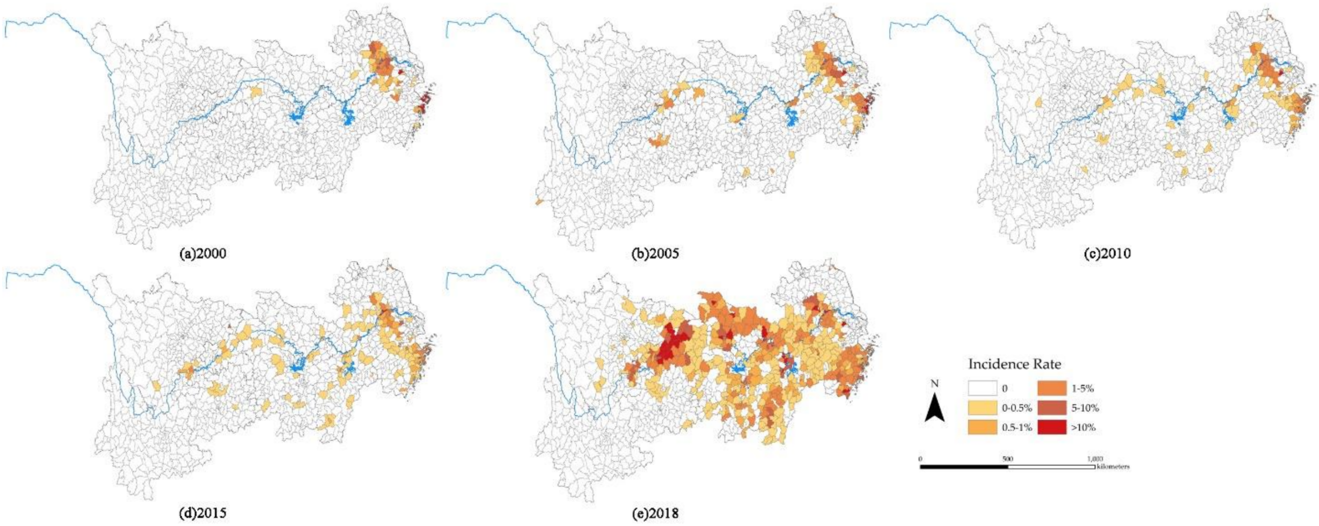


Figure 4. (**a**–**e**) the incidence of PWD at the county level in the Yangtze River Basin from 2000 to 2018.

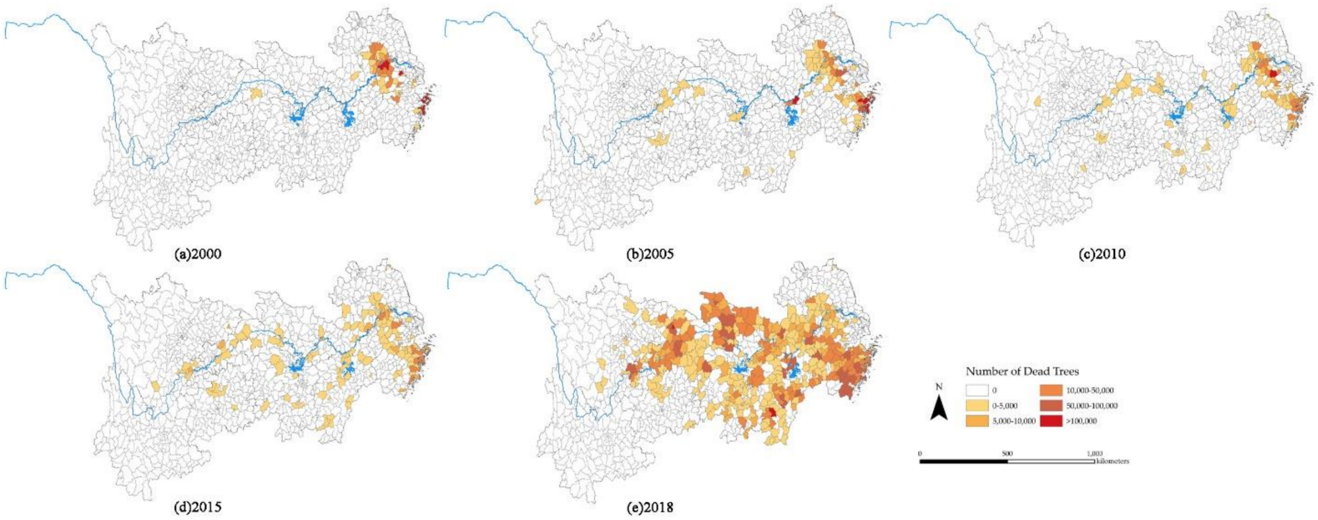


Figure 5. (**a**–**e**) number of dead trees at the county level in the Yangtze River Basin from 2000 to 2018.

3.4. Spatiotemporal Aggregation Analysis of PWD

PWD in the Yangtze River Basin was scanned annually from 2000 to 2018, and a primary cluster and more than five secondary clusters were obtained (Figure 6). The 19 years were divided into four stages for further analysis and study: (1) 2000–2005 is the first stage. The primary cluster was located in the coastal area of Zhejiang Province, and the gathering radius of this cluster was reduced. The secondary cluster located in Jiangsu Province disappeared, and several secondary clusters appeared at the junction of Jiangsu Province and Anhui Province. In addition, the clusters began to distribute westward along the Yangtze River basin. For the first time, a cluster appeared in Chongqing. (2) The second stage comprises 2005–2010. In this stage, the centre of gravity of the primary cluster was unchanged, and its gathering radius increased, becoming the secondary cluster. The primary cluster formed in Jiangsu Province, and several important secondary clusters were formed at the junction of the Jiangsu and Anhui provinces, the junction of the Zhejiang and Jiangsu provinces, and the coastal area of Zhejiang Province. (3) The third stage covers 2010–2015. The accumulation radius of the Jiangsu primary cluster increased significantly in this stage, while that of the Zhejiang secondary cluster decreased, and the centre of gravity moved north. In the middle and upper reaches of the Yangtze River, several secondary clusters were distributed along the Yangtze River Basin. (4) The final stage comprises 2015–2018. The clusters were distributed along the Yangtze River Basin, with multipoint outbreaks. The primary cluster moved from Jiangsu Province to Chongqing. Three important secondary clusters were identified in Chongqing, and two important secondary clusters were observed in Hubei.

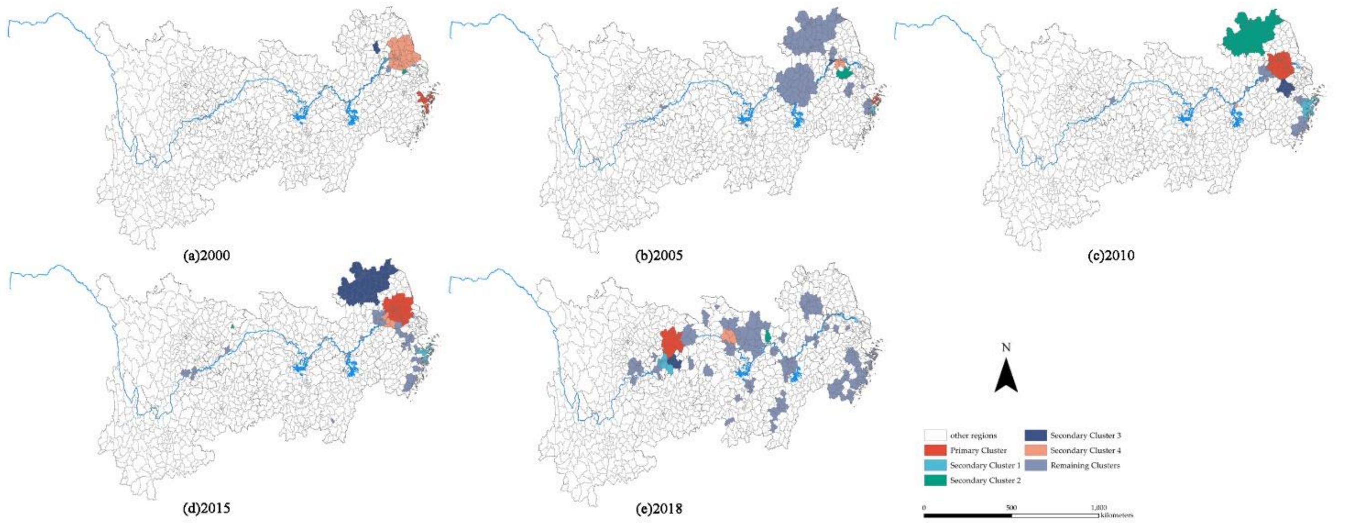


Figure 6. (**a**–**e**) annual spatial scanning results.

The spatiotemporal agglomeration scanning of the disaster-stricken areas in the Yangtze River Basin from 2000 to 2018 revealed a primary cluster and three secondary clusters (Figure 7). The primary cluster was located in the coastal area of Zhejiang Province, and its concentrated incidence time was 2000–2008. The first secondary cluster (secondary cluster 1) was distributed in Chongqing, secondary cluster 2 was located in Hubei Province, and secondary cluster 3 was located in the northern area of Jiangxi Province. The concentrated incidence times of the three secondary clusters occurred in 2018.

Apart from the older gathering areas in Zhejiang Province, the newer gathering areas were all distributed along the Yangtze River Basin. According to the spatiotemporal scanning results, PWD showed high-agglomeration distributions in the Zhejiang, Chongqing, Hubei, and Jiangxi provinces in the past 19 years. The three agglomeration areas of Chongqing, Hubei, and Jiangxi represented new clusters with concentrated outbreaks in 2018 and were distributed along the Yangtze River. The spatiotemporal scanning results of the county-scale disasters showed the same changes and previously described statistical results. Zhejiang Province suffered continuous disasters over the 19 studied years. The disaster area remained high from 2000 to 2008, and the number of affected counties continued to increase. This area represents the first batch of infested areas in inland China. In 2018, PWD broke out at multiple points along the Yangtze River and spread continuously. Chongqing, Hubei, and Jiangxi were the most severely affected areas, and Chongqing showed the worst conditions. The distribution of disasters and the timing of the concentrated outbreaks were consistent with the timing and spatial distribution of the disease and pest, as shown by simple spatial scanning of "plaques". These two consistencies mutually confirm the outbreak and spreading patterns of the disease in infected clusters.

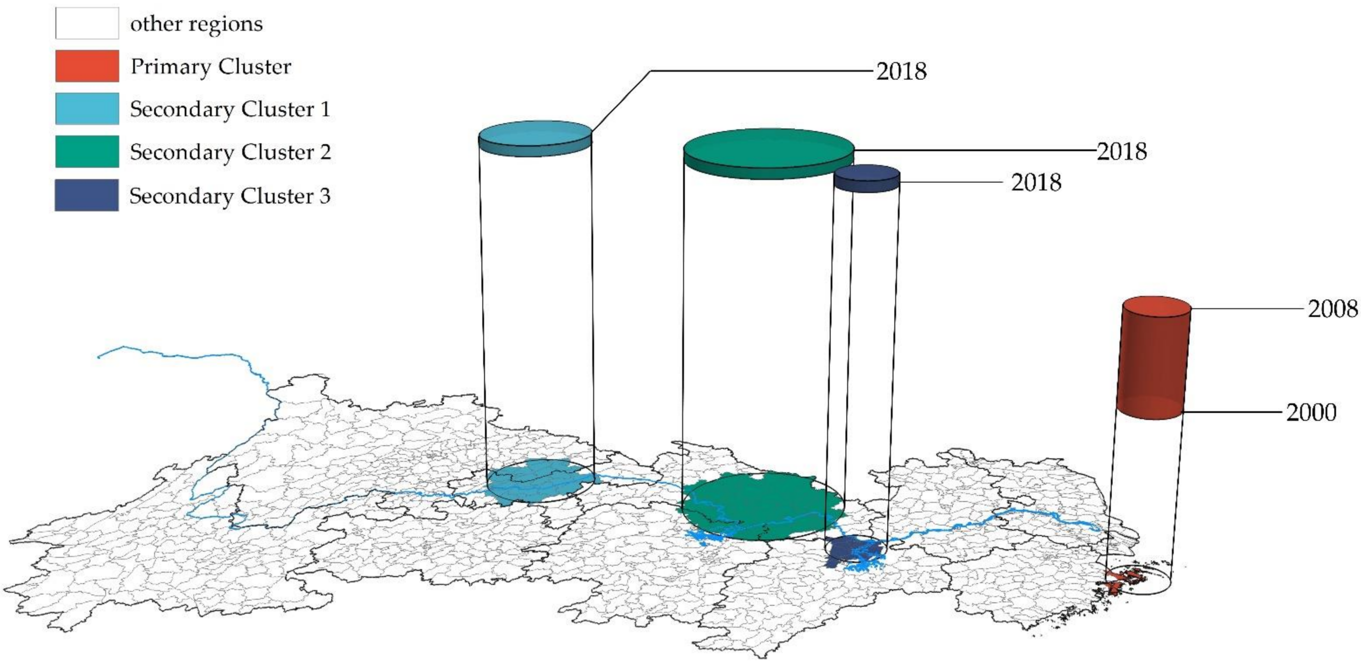


Figure 7. Spatiotemporal scanning results of PWD in the Yangtze River Basin (3D).

4. Discussion

In this paper, with the help of spatiotemporal visualization analysis and spatiotemporal scanning statistics technology, according to the data of PWD disaster areas and dead trees and their spatial distribution characteristics, the prevalence of PWD in the Yangtze River Basin is explored, and the law and characteristics of the spread of PWD from 2000 to 2018 are intuitively revealed.

From 2000 to 2018, PWD in 11 provinces of the Yangtze River Basin showed an "increasing-decreasing-increasing" trend, and PWD increased explosively in 2018. The area affected by PWD generally showed a trend of first declining and then increasing. The observed changes in the numbers of dead trees can be divided into three stages: a reduction period, a stable period, and an outbreak period. The number of affected counties showed an overall "growth-steady-outbreak" trend. The Yangtze River Basin has a suitable climate and is in a suitable area for the PWN, with extremely high potential risks [34]. The development of PWD is closely related to the monitoring level of PWD in China. The peak period of PWD research in China occurred after 2000, and research on this topic specifically accumulated from 2006 to 2013. Before 2006, China developed molecular detection technology for PWD, successfully applied it in production, and promoted its use throughout the country. In 2009, the promotion and popularization of automatic molecular detection technology were realized [35]. Monitoring PWD is the prerequisite and basis for "early detection, early reporting, early blockade, early elimination, and treatment". If the gold prevention and control period standards are missed at the initial stage of an epidemic, the difficulty of prevention and control are greatly increased. In recent years, China's prevention and control measures have been improved, and PWD monitoring has intensified, but the monitoring capacity is still insufficient, and cases of untimely reporting still occur [36]. In the process of removing and curing diseased trees in newly infected areas, ultra-intensive and large-scale logging has been adopted. If the diseased trees are not well supervised, this method will accelerate the spread of PWD [35]. An epidemic broke out in a large area in 2018. The national average temperature in the spring of that year was the highest value recorded since 1961, and the precipitation amounts in the southern part of the Yangtze River and most of southern China were less than those recorded in previous years. The climate was dry [37], and drought in the Jiangnan region continued in summer [38]. Summer is the peak season of pinewood nematode activity. Dry and hot summer conditions promote the reproduction of pinewood nematodes, and PWD symptoms develop rapidly [39]. In addition, six districts and counties, including Fuling and Fengdu in Chongqing, experienced “mass death” epidemics. These results are closely related to governance errors associated with the streets and forest farms of the townships.

The spread of PWD in the Yangtze River Basin showed a “jumping propagation-multi-point outbreak-point to surface spread” pattern and moved west along the river. The transmission of PWD in China relies on human activities and natural transmission. As the main method of transmission, human activities have caused 75% of the epidemics in China [35]. The carriers of PWD include infested wood, packing boxes, cable reels, and optical cable reels. Natural transmission relies on its vector insect, Monochamus alternatus. Since China’s accession to the WTO in 2001 and the globalization of international trade, the risk of PWD being imported into non-epidemic areas of China from other countries has increased [40]. All provinces in the Yangtze River Basin have suffered from PWD. The epidemic situation was more severe in the lower reaches of the Yangtze River than elsewhere in China, but this situation has been controlled to a certain extent. The spread of epidemics in the middle and upper reaches of the Yangtze River is not optimistic. PWD expanded in 2013 and broke out in 2018. Since 2013, the Yangtze River Basin has gradually accelerated its rise into a national strategy [41]. The rapid development of communication, electric power, and transportation industries as well as and other industries has increased logistics paths, increased fluxes, and accelerated the speed of transport, accelerating the spread of PWD [42]. In the construction of relevant projects, major interprovincial transfers of untreated or incompletely treated diseased logs, timber, fuel wood, and packaging materials have led to outflows of diseased wood. PWD has spread along the Yangtze River, forming a major disaster area in Chongqing. In 2018, PWD broke out in a large area, and this study revealed the pattern of its spread. To explain the reasons for these patterns in depth, it is necessary to collect more detailed data, such as PWD incidence data at the forest sub-level scale. Due to the limitation of the content of one study, we will deeply analyse the PWD production mechanism in the next study.

According to the research results, important clusters were concentrated in the Jiangsu-Zhejiang area from 2000 to 2015, forming a cluster of Jiangsu and Zhejiang. The centre of gravity within this cluster remained unchanged, but the radius continually increased. This phenomenon is closely related to the regional economic level. The PWN first appeared in Nanjing, Jiangsu Province, in 1982 and then relied on the host insect of the PWN to spread to neighbouring counties within short distances. The Jiangsu-Zhejiang-Shanghai area has a developed economy, convenient transportation, and frequent trade, and this region is undergoing rapid electric power and communication industry development, forming a centre for the spread of PWD in China [40]. From 2015 to 2018, important clusters were concentrated in Chongqing, and the centre of epidemic gravity gradually moved westward, forming the Chongqing cluster. The rest of the clusters were distributed along the Yangtze River, with the gathering radius gradually increasing and exploding at multiple points. According to the research results obtained herein, the population of the PWN in mainland China can be divided into two types. One type spread from Guangdong to Anhui and Zhejiang; the other spread from Guangdong to Jiangsu and then to Hubei, Chongqing, Guizhou, Anhui, and other places [43]. The influx of unqualified-quarantine goods resulting from transformations of the power grid and communication lines has accelerated the expansion of PWD from one point to a distributed area in the original epidemic area.

From 2000 to 2018, PWD showed high aggregation in the four regions of Zhejiang, Chongqing, Hubei, and Jiangxi. The three clusters in Chongqing, Hubei, and Jiangxi represented new concentrated case areas in 2018, and these cluster areas were all distributed along the Yangtze River. Studies have shown that the root cause of the introduction of PWD into Chongqing is the introduction of pinewood packaging materials [12]. In 2018, PWD broke out at multiple points along the Yangtze River Basin and spread continuously. The Yangtze River Basin is located in southern China. Most areas have subtropical monsoon climates with suitable temperatures and are highly suitable for the PWN. The PWN has a high and strong reproductive potential. When it enters a newly suitable area, the PWN multiplies and spreads rapidly. The pines in Jiangxi Province are mainly Masson pine and slash pine. Masson pine is a native tree species in Jiangxi Province. It has the characteristics of adaptability, strong stress resistance, and fast growth, providing suitable conditions for the spread of PWD. Monochamus alternatus, the host of the PWN, is widely distributed in Jiangxi Province, increasing the possibility of PWD spreading within the province.

Since the introduction of PWD, China has gained an in-depth understanding of the occurrence and spread of the disease; has made significant progress in understanding many aspects of PWD, such as its physiological mechanisms, diffusion modes, and control technology; and has also achieved positive results in PWD control projects. A total of 162 county-level epidemic areas have been removed, and the current infection rate of pine forests is also controlled below 3%. However, the situation of the rapid spread of PWD is very serious, many misunderstandings and blind spots still exist in the prevention and control of PWD, and scientific, reasonable, economical, and effective prevention and control methods still need to be improved. The control of PWD has three key links: disease quarantine and epidemic monitoring, infested wood treatment, and vector insect control [35]. Since 75% of PWD spread at large scales and long distances is caused by human activities, ground-based epidemic monitoring and remote sensing-based monitoring can now be combined, and high-resolution satellite images and drone impacts can be widely used to monitor the health of pine trees. In the future, prevention and control measures for PWD need to pay more attention to the systematic management of disaster prevention and control, including ecological restoration measures for infected pine forests and the healthy cultivation of high-risk pine forests.

There are also some shortcomings in this study. First, when calculating the incidence of PWD, because the current annual area of the pine trees is difficult to obtain and inaccurate, the vegetation coverage index is extracted using December NDVI data to calculate the vegetation area as the area of pine trees. In addition, this study mainly analyses the spreading process of PWD in the Yangtze River Basin without considering biological propagation characteristics or analysing the temporal and spatial distributions of the PWN and its host species.

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