Analysis of Influencing Factors of Pine Wood Nematode Disease in Lu'an City Based on GIS

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Abstract [**Objectives**] The paper was to figure out the distribution of *Monochamus alternatus* in the stumps of pine wood nematode infected wood in Lu'an City and to provide a theoretical and practical basis for differentiated prevention and control of pine wood nematode disease in the future. [**Methods**] The factors influencing the number of epidemic small classes and infected plants in all counties and districts of Lu'an City were analyzed by GIS method, and the number of worms and wormholes of *M. alternatus* inside and outside the stumps of pine wood nematode infected wood in Lu'an City were investigated on the spot. [**Results**] There were 98, 40, 54, 781, 193, 268 and 34 epidemic small classes of pine wood nematode disease, and 7 241, 6 099, 9 532, 39 161, 11 079, 49 876 and 4 853 infected plants in Yu'an District, Jin'an District, Yeji District, Shucheng County, Huoshan County, Jinzhai County and Huoqiu County, respectively. Pine wood nematode disease in Lu'an City mostly occurred in Huoshan County, Shucheng County and Jinzhai County, with relatively high altitude, paddy soil, the annual precipitation higher than 2 062 mm, and the annual average temperature lower than 16.2 ℃. The number of diseased plants of pine wood nematode disease was positively correlated with altitude and annual precipitation, and was negatively correlated with annual average temperature. The number of worms and wormholes in pine wood nematode infected wood was very small at different altitudes, stump heights and stump diameters. [**Conclusions**] The pine wood nematode infected wood can be differentially processed after stump treatment, and stumps can be peeled. The results will provide a theoretical and practical basis for differentiated prevention and control of pine wood nematode disease in the future.

Key words GIS; Pine wood nematode disease; Influencing factor; Control measure; Lu'an City

1 Introduction

Pine wood nematode disease, also known as pine wilt disease, has spread at an extremely fast speed since its discovery in China. In just a few decades, the epidemic area has become larger and larger, and now reaches nearly 2 million hm^2, posing a great threat to the stability of the ecosystem. Due to the wide range of the disease, rapid spread, and difficulties in prevention and control, the harm caused by the disease has gradually formed new characteristics. Natural transmission and man-made transmission are two major transmission routes of pine wood nematode disease[1].

With the increasing awareness of ecological civilization, the prevention and control of pine wood nematode disease has become a focus of global attention. The physiological characteristics, pathogenesis, prevention and control principle and post-disease control methods of pine wood nematode disease and its vector insects have been systematically studied all over the world[2-4]. Studies on pathogenic pathogens mainly focus on the pinewood nematode, *Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle, including its biological characteristics and population dynamic changes in different ecosystems at different periods[5-6]. In the study of influencing factors, environmental factors and human impact factors are major influencing factors. In terms of control methods, pathogen prevention and control and strengthening quarantine are major directions. However, these studies are all about the pathogenesis and pre-epidemic control of pine wood nematode disease, and there are few treatment methods of pine wood nematode infected wood. Meantime, the few reviews are generally based on the summary of existing research results[7], and less efforts have been dedicated to the investigation and analysis of processed pine wood nematode infected wood to clarify the best treatment method. At present, great achievements have been made in the theoretical basis and technical methods of pine wood nematode disease research[8]. Cleaning pine wood nematode infected wood is the main measure to control pine wood nematode disease. Stump treatment is more complex, time-consuming and laborious, and the film, wire mesh and drugs required for stump treatment have a certain impact on the surrounding environment, posing a certain security risks to the surrounding farmers. Relevant survey on stumps of pine wood nematode infected wood was conducted in the study. Based on the actual situation of Lu'an City, GIS analysis was em-

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ployed to analyze the factors influencing the number of epidemic small classes and infected plants in all counties and districts of Lu'an City, compare the number of worms and wormholes inside and outside stumps after stump treatment of pine wood nematode disease, and analyze the prevention and control measures, in order to provide a theoretical and practical basis for differentiated prevention and control of pine wood nematode disease in the future.

2 Overview of survey area and research methods

2.1 Overview of survey area The survey was conducted in Lu'an City, Anhui Province, 115°20′ – 117°14′ E, 31°01′ – 32°40′ N. The terrain is high in the southwest and flat in the northeast, showing a trapezoidal distribution. It belongs to humid monsoon climate with significant monsoon, cold winter and hot summer, rich heat, and good coordination of light, heat and water. The area is featured by four distinct seasons, mild climate, moderate rainfall, sufficient light, long frost-free period. The annual sunshine is 2 000 – 2 300 h, and the annual average temperature is 15.6 ℃; the annual average rainfall is about 1 100 mm, mainly concentrated from May to August, accounting for 55% of the total annual precipitation.

2.2 Research methods

2.2.1 Statistics on the spatial distribution of the epidemic. The spatial distribution of the epidemic was obtained using multi-source and multi-resolution remote sensing images. According to the color, shape and size of different ground objects reflected in remote sensing images, the physiological and ecological characteristics and canopy spectrum of pine infected with pine wood nematode disease were analyzed.

2.2.2 Statistics on the number of epidemic small classes. Based on the extracted data results, the epidemic areas were divided, and the locations of pine wood nematode disease were divided into several small classes for statistical analysis.

2.2.3 Determination of the number of worms and wormholes in stump of infected wood. The survey sites were inspected regularly and samples were collected from different parts of pine wood nematode infected wood and stumps of dead wood. After selective stumping in accordance with the *Pine Wood Nematode Disease Control Technical Program* (Revised Edition) and *Management Measures for Pine Wood Nematode Disease Epidemic Areas and Infected Wood* issued by the State Forestry Administration, the height and ground diameter of stumps were measured and recorded. The harvesting stumps were cut off, and the number of worms and wormholes were observed and recorded statistically.

2.3 Data source, processing and analysis Based on the data provided by the Lu'an Forestry Bureau, 1 960 stumps of infected wood were randomly selected from different regions, different tree mixing patterns, different altitudes and different ground diameters in three districts and four counties of Lu'an City for data analysis. In order to ensure that the data were not homogeneous, the data analyzed involved the situation of each epidemic point in all counties and districts.

The ground diameter and height of stumps and the number of worms and wormholes were statistically calculated by Microsoft Excel 2019. The distribution of pine wood nematode disease, number of epidemic small classes and infected plants, ecological factor analysis, and nuclear density analysis of disease and pest intensity in all counties and districts of Lu'an were plotted by GIS.

3 Results and analysis

3.1 Spatial distribution of infected wood As shown in Fig. 1, the number of townships with pine wood nematode infected wood and spatial distribution of forest farms in Yu'an District, Jin'an District, Yeji District, Shucheng County, Huoshan County, Jinzhai County and Huoqiu County were 9 townships and 1 forest farm (forest seed farm), 10 townships and 1 forest farm (Yanshan forest farm), 1 township and 1 forest farm (Kanhualou forest farm), 15 townships and 1 forest farm (Wanfoshan state-owned forest farm), 15 townships and 1 forest farm (state-owned forestry farm), 20 townships, 2 townships and 1 forest farm (Xishan forest farm), with a total of 72 townships and 6 forest farms.

3.2 Number of epidemic small classes and infected plants in all counties and districts As shown in Fig. 2, the number of infected plants and epidemic small classes in various counties and districts of Lu'an City were 7 241 plants and 98 small classes in Yu'an District, 6 099 plants and 40 small classes in Jin'an District, 9 532 plants and 54 small classes in Yeji District, 39 161 plants and 781 small classes in Shucheng County, 11 079 plants and 193 small classes in Jinzhai County, 49 876 plants and 268 small classes in Huoshan County, 4 853 plants and 34 small classes in Huoqiu County, with a total of 127 841 plants and 1 468 small classes in the whole city.

3.3 Relationship with ecological factors

3.3.1 Altitude. The growth and development of plants are affected by altitude change. Atmospheric pressure varies at different altitudes, which leads to a large difference in the content of various gases in the air, affecting the growth and development of plants and animals. Pine wood nematode disease in Lu'an mostly occurred in relatively high altitude areas, especially in Huoshan County, Shucheng County and Jinzhai County (Fig. 3).

3.3.2 Soil type. Soil offers a growth environment for plant roots, and provides heat preservation, fixation, nutrition and other functions for plants. A root system with deep distribution can absorb more water and fertilizer, and thus provide continuous power for plant growth. The soil type in Lu'an City is mainly composed of yellow brown soil, yellow soil and paddy soil. Yellow brown soil is mainly distributed in areas with higher temperature and more rainfall. Yellow soil has obvious hierarchy, and its agricultural soil profile consists of plough layer, subsoil layer and parent material layer. Yellow soil not only has the necessary nutrients for pine

Fig. 1 Spatial distribution of pine wood nematode infected wood in Lu'an

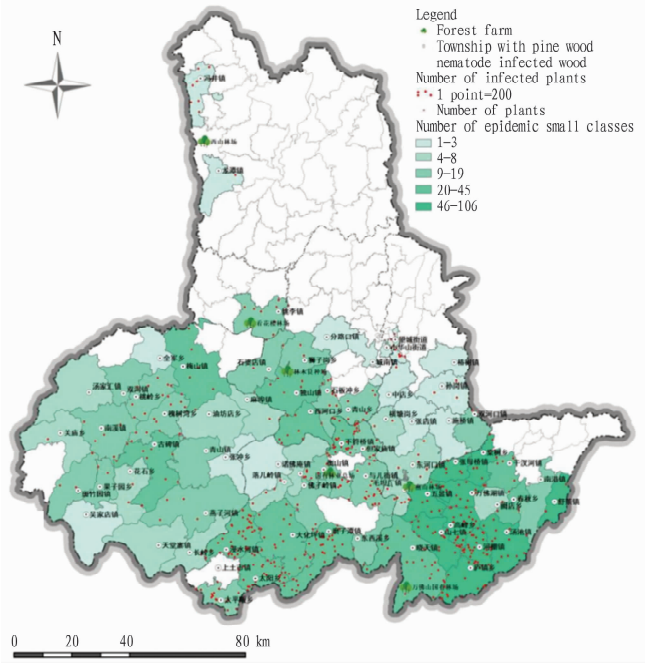

Fig. 2 Visualization of the number of epidemic small classes and plants in all counties and districts of Lu'an City

growth, but also satisfies the growth habit of pine. Paddy soil is inundated for a long time due to natural soil formation and human factors, and can not provide enough oxygen for the normal life activities of pine trees growing in it. The excess water in paddy soil is not conducive to the reproductive growth of pine trees, and leads to strong disease susceptibility and weak disease resistance of pine trees, thereby easily causing the occurrence and spread of pine wood nematode disease.

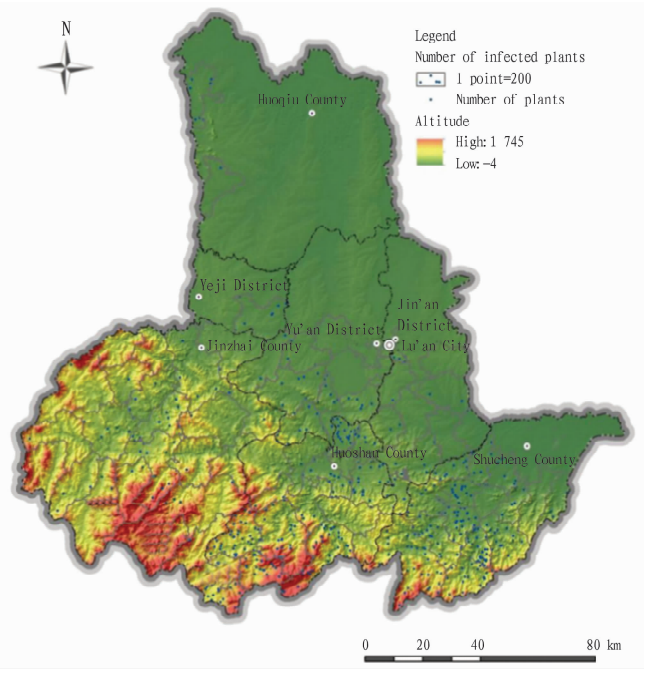

Fig. 3 Effect of altitude on pine wood nematode disease in Lu'an City

Soil provides indispensable water and fertilizer conditions for plant growth and development. It is an important factor affecting plant growth potential, and directly determines the susceptibility and resistance of plants to diseases. Pine wood nematode disease in Lu'an City mostly occurred in areas with paddy soil, especially in Huoshan County and Shucheng County. There was large epidemic area of *B. xylophilus*, causing heavy damage (Fig. 4).

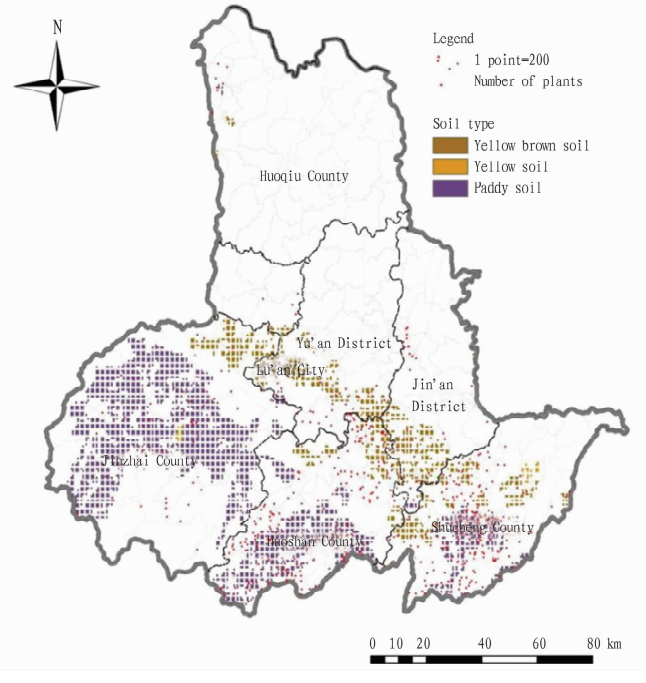

Fig. 4 Effect of soil type on pine wood nematode disease in Lu'an City

3.3.3 Annual precipitation. Water provides a solvent for transporting nutrients to plants, and it is an important component of plants and an indispensable power source for plants to carry out transpiration, respiration, photosynthesis and other life activities. Water is also an essential material condition for life activities of *B. xylophilus* and *Monochamus alternatus*.

The average annual precipitations of Yu'an District, Jin'an District, Yeji District, Shucheng County, Huoshan County, Jinzhai County and Huoqiu County were 2 020, 1 886, 2 012, 2 062, 2 415, 2 320 and 1 608 mm, respectively. Due to developed cuticle of needle, *Pinus massoniana* can grow in stony, shallow soil arid habitat, and can tolerate water shortage environment without injury. *P. massoniana* is a xerophytic plant. Excessive soil moisture is bad for its growth, and further affects the occurrence and spread of pine wood nematode disease. Pine wood nematode disease in Lu'an mostly occurred in areas with high annual precipitation, especially in Huoshan County and Shucheng County with relatively heavy precipitation (Fig. 5).

3.3.4 Annual average temperature. The optimum temperature for the survival of *M. alternatus* and *B. xylophilus* is 25 ℃. The eggs of *B. xylophilus* can be incubated at 25 ℃ after 30 h, and one generation can be completed in 3 d. *B. xylophilus* could not develop normally at low temperature, but can not reproduce normally at high temperature. The optimum breeding temperature of *M. alternatus* is 25 – 30 ℃. When the temperature is low, the hugging rate and mating rate of *M. alternatus* adults decrease. When the temperature drops to 18 ℃, the adults will remain dormant. Low temperature also affects the development of female ovaries. Therefore, when the temperature is 25 ℃, it is most suitable for the propagation of *M. alternatus* and *B. xylophilus*, and pine trees are more vulnerable to pine wood nematode disease.

The average annual temperatures in Yu'an District, Jin'an District, Yeji District, Shucheng County, Huoshan County, Jinzhai County and Huoqiu County were 16.6, 16.6, 16.2, 15.2, 14.8 and 16.5 ℃, respectively (Fig. 6). Most pine trees are light-loving species with weak shade tolerance. Areas with low average annual temperature are unable to meet the pine tree's growth habit of warm preference and full light, resulting in pine trees susceptible to diseases and pests. Pine wood nematode disease in Lu'an City mostly occurred in areas with relatively low annual average temperature, especially in Huoshan County and Shucheng County, which had high incidence and high epidemic density. Huoqiu County with relatively high annual average temperature had a low incidence and small epidemic scope.

3.4 Comparison of the number and spatial distribution of worms and wormholes in pine wood nematode infected wood

The proportion of worms and wormholes inside and outside the stumps in Yeji District and Huoqiu County was low, indicating that pine trees in these two counties had strong anti-epidemic ability, and the environment in this area was not suitable for the growth and life of *M. alternatus*; in the outer Yu'an district and Jin'an district, there were more worms and wormholes inside and outside the stumps, indicating that the environment in this area was suitable for the growth and breeding activities of *M. alternatus*; while in Shucheng County, Huoshan County and Jinzhai County, the proportions of worms and wormholes inside and outside the stumps were moderate, indicating that there may be some factors restricting the growth and reproduction of *M. alternatus* in these areas, and thus the reproduction and growth activities of *M. alternatus* were affected (Table 1). There was dense distribution of pine wood nematode disease in Yu'an District, Shucheng County and Huoshan County, and relatively sparse distribution in Jin'an District, Yeji District, Jinzhai County and Huoqiu County (Fig. 7).

Table 1 Number and proportion of worms and wormholes inside and outside the stumps in counties and districts of Lu'an City

Location	Outside the stump		Inside the stump		Number of surveyed plants // plant	Outside the stump		Inside the stump	
	Number of worms individual	Number of wormholes individual	Number of worms individual	Number of wormholes individual		Proportion of worms // %	Proportion of wormholes // %	Proportion of worms // %	Proportion of wormholes // %
Yu'an District	86	143	33	122	200	43.00	71.50	16.50	61.00
Jin'an District	55	186	9	28	150	36.70	124.00	6.00	18.70
Yeji District	0	1	1	13	80	0.00	1.30	1.30	16.30
Shucheng County	67	173	52	94	730	9.20	23.70	7.10	12.90
Huoshan County	92	84	7	21	390	23.60	21.50	1.80	5.40
Jinzhai County	20	176	8	10	340	5.90	51.80	2.40	2.90
Huoqiu County	0	35	0	0	70	0.00	50.00	0.00	0.00
Average	46	114	16	41	280	16.91	49.11	5.01	16.74

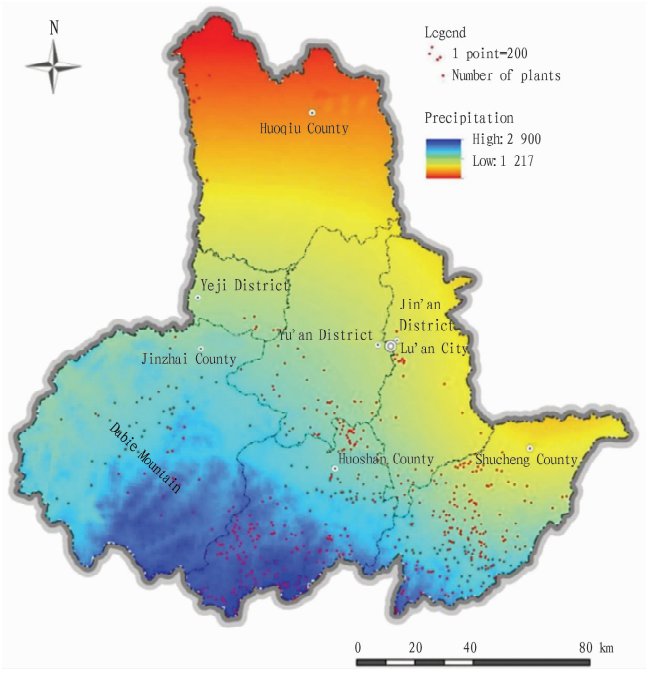

Fig. 5 Effect of annual precipitation on pine wood nematode disease in Lu'an City

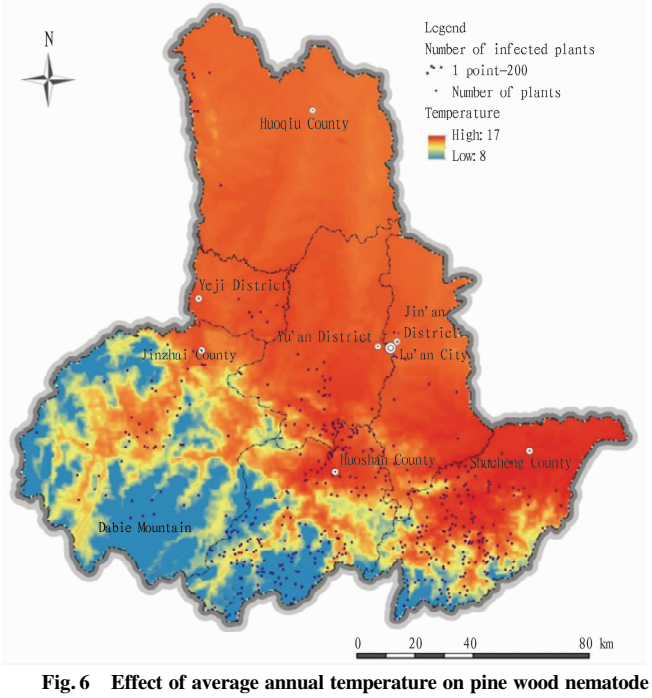

Fig. 6 Effect of average annual temperature on pine wood nematode disease in Lu'an City

3.5 Relationship of worms and wormholes of infected wood with altitude, stump height and stump diameter

3.5.1 Relationship with altitude. As shown in Table 2, when the altitude was less than 0 m and greater than 200 m, the number of worms and wormholes inside and outside the stumps was less than 100. Both the altitude less than 0 m and greater than 200 m showed fewer worms and wormholes, with insignificant difference. Therefore, in order to achieve good control effect and save cost, it is suggested to carry out a series of pest control treatments at the altitude of 0 – 200 m.

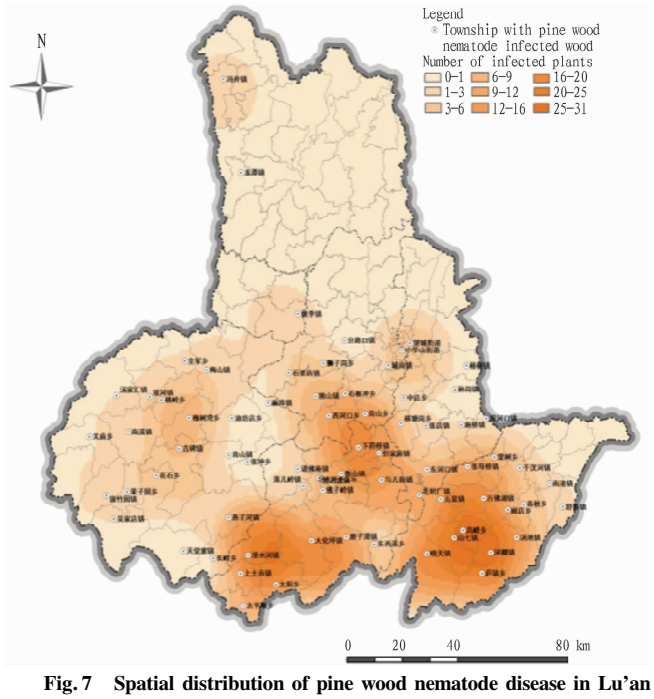

Fig. 7 Spatial distribution of pine wood nematode disease in Lu'an City

3.5.2 Relationship with stump diameter. The number of worms and wormholes was obviously less when the ground diameter of stumps was less than 10 cm or greater than 30 cm. Different stump diameters were analyzed, and the results are shown in Table 3. It can be concluded that there was no significant difference in the number of worms and wormholes when the ground diameter of stumps was less than 10 cm or greater than 30 cm (Table 3).

3.5.3 Relationship with stump height. The *Measures for the Management of Forest Felling and Renewal* stipulates that the height of stump shall not exceed 10 cm[9]. Through investigation and analysis, it was found that the number of worms and wormholes was less than 100 when the height of stump was greater than 4 cm. The number of worms and wormholes in most of the survey sites was less than 5. Especially when the height of stump was greater than 5 cm, the number of worms inside and outside the stump was 0, and the number of wormholes was also very rare (Table 4).

4 Conclusions and discussion

4.1 Conclusions There were 98, 40, 54, 781, 193, 268 and 34 epidemic small classes of pine wood nematode disease in Yu'an District, Jin'an District, Yeji District, Shucheng County, Huoshan County, Jinzhai County and Huoqiu County. Shucheng County had the largest number of epidemic small classes, followed by Jinzhai County. There were 7 241, 6 099, 9 532, 39 161, 11 079, 49 876 and 4 853 plants of *P. massoniana* infected by pine wood nematode disease in Yu'an District, Jin'an District, Yeji District, Shucheng County, Huoshan County, Jinzhai County and Huoqiu County, suggesting that Jinzhai County, Shucheng County and Huoshan

County had larger number of infected plants. Pine wood nematode disease mostly occurred in Huoshan County, Shucheng County and Jinzhai County, with relatively high altitude, paddy soil, the annual precipitation higher than 2 062 mm, and the annual average temperature lower than 16.2 ℃. The number of worms and wormholes in pine wood nematode infected wood was very few at different altitudes, stump heights and stump diameters. The results indicate that the stumps of pine wood nematode infected wood can be treated differently in the future, such as peeling of stumps. The conclusion can provide a theoretical and practical basis for differentiated prevention and control of pine wood nematode disease in the future.

Table 2 Comparison of the number of worms and wormholes inside and outside the stumps of pine wood nematode infected wood at different altitudes

Altitude range//m	Outside the stump		Inside the stump		Number of surveyed plants//plant
	Number of worms//individual	Number of wormholes//individual	Number of worms//individual	Number of wormholes//individual	
$x \leqslant 0$	3	5	1	4	20
$0 < x \leqslant 100$	153	501	91	258	843
$100 < x \leqslant 200$	66	105	7	18	482
$200 < x \leqslant 300$	12	53	6	6	187
$300 < x \leqslant 400$	9	68	5	2	163
$400 < x \leqslant 500$	0	15	0	0	70
$500 < x \leqslant 600$	75	38	0	0	140
$600 < x \leqslant 700$	2	13	0	0	20
$700 < x \leqslant 800$	0	0	0	0	25
$800 < x \leqslant 900$	0	0	0	0	0
$900 < x \leqslant 1\,000$	0	0	0	0	0
$1\,000 < x \leqslant 1\,100$	0	0	0	0	10

Table 3 Comparison of the number of worms and wormholes inside and outside the stumps of pine wood nematode infected wood with different stump diameters

Stump diameter//cm	Outside the stump		Inside the stump		Number of surveyed plants//plant
	Number of worms//individual	Number of wormholes//individual	Number of worms//individual	Number of wormholes//individual	
$0 < x \leqslant 10$	3	7	1	2	31
$10 < x \leqslant 20$	70	238	20	69	934
$20 < x \leqslant 30$	201	403	59	139	821
$30 < x \leqslant 40$	28	128	30	78	158
$40 < x \leqslant 50$	17	2	0	0	14
$50 < x \leqslant 60$	1	20	0	0	2

Table 4 Comparison of the number of worms and wormholes inside and outside the stumps of pine wood nematode infected wood with different stump heights

Stump height//cm	Outside the stump		Inside the stump		Number of surveyed plants//plant
	Number of worms//individual	Number of wormholes//individual	Number of worms//individual	Number of wormholes//individual	
$0 < x \leqslant 1$	167	178	9	25	807
$1 < x \leqslant 2$	86	244	57	133	567
$2 < x \leqslant 3$	32	157	7	40	302
$3 < x \leqslant 4$	9	152	34	85	150
$4 < x \leqslant 5$	26	56	3	2	120
$5 < x \leqslant 6$	0	3	0	0	5
$6 < x \leqslant 7$	0	8	0	3	4
$7 < x \leqslant 8$	0	0	0	0	3
$8 < x \leqslant 9$	0	0	0	0	2

4.2 Discussion In order to control the spread and expansion of pine wood nematode disease, the following measures can be taken. First, quarantine should be strengthened to eliminate the source of infection. All pine trees and their products entering the territory of China should be strictly quarantined and inspected. Second, *M. alternatus* and *B. xylophilus* must be prevented and controlled. *M. alternatus* and *B. xylophilus* in epidemic stumps are important infectious sources of pine wood nematode disease[10-11]. Third, publicity must be strengthened. At present, pine wood nematode disease has caused serious harm to forest resources and ecological environment[12]. The understanding and prevention of pine wood nematode disease should be improved. Finally, the infected wood should be

dealt with properly and promptly, and supervision should be strengthened. All felled pine trees should be managed as infected wood[13].

In this study, the number of plants infected by pine wood nematode disease was positively correlated with altitude and annual precipitation, and was negatively correlated with annual average temperature. It can be seen that pine wood nematode disease is prone to occur in areas with high altitude, high annual precipitation and relatively low annual average temperature. Therefore, in the subsequent control of pine wood nematode disease, we should try best to create a dry, airy and transparent environment in *P. massoniana* forest. The treatment of wood infected by pine wood nematode disease is extremely important, and there are many ways to deal with stump, such as treating with strains that can restrict the growth and reproduction of *B. xylophilus*[14], or digging stump and burning, peeling and digging for worms and other measures. At present, cleaning of infected wood is the major measure against pine wood nematode disease, involving multiple links such as felling, cleaning and disinfestation. Capital investment directly affects the effectiveness of prevention and control work and the quality of eradication against pine wood nematode disease[15]. Lu'an City invests more than 2 million yuan every year in film, wire mesh and drugs needed for the stump treatment of pine wood nematode infected wood, which also causes environmental pollution to the surrounding environment. The results of this study showed that the number of worms inside and outside the stumps of pine wood nematode infected wood was very small, almost negligible. Therefore, in order to effectively prevent and control pine wood nematode disease and reduce capital investment and pollution to the surrounding environment, the follow-up treatment after the stumping of pine wood nematode infected wood can be stopped or reduced in the future, and differentiated treatment can be carried out on the stump, such as peeling of stumps. These results can provide a theoretical and practical basis for the differential prevention and control of pine wood nematode disease in the future.

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