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RESEARCH ARTICLE

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Response of pine forest to disturbance of pine wood nematode with interpretative structural model

Abstract Pine wood nematode (PWN, *Bursaphelenchus xylophilus*), originating from North America, causes destructive pine wilt disease. Different pine forest ecosystems have different resistances to *B. xylophilus*, and after its invasion, the resilience and restoration direction of different ecosystems also varies. In this study, an interpretative structural model was applied for analyzing the response of pine forest ecosystem to PWN disturbance. The result showed that a five-degree multi-stage hierarchical system affected the response of the pine forest ecosystem to PWN disturbance, in which direct affecting factors are resistance and resilience. Furthermore, the analysis to the 2nd, 3rd and 4th degree factors showed that not only does distribution pattern of plant species and pine's ecological features affect the resistance of pine forests' ecosystem, but removal of attacked trees and other measures also influence the resistance through indirectly affecting the damage degree of *Monochamus alternatus* and distribution pattern of plant species. As for resilience, it is influenced directly by soil factors, hydrology, surrounding species provenance and biological characteristics of the second and jointly dominant species, and the climate factors can also have a direct or indirect effect on it by affecting the above factors. Among the fifth elements, the elevation, gradient and slope direction, topographical factors, diversity of geographical location and improvement of prevention technology all influence the response of pine forest ecosystem to PWN disturbance.

Keywords *Bursaphelenchus xylophilus*, disturbance, interpretative structural model, resistance, resilience

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1 Introduction

The pine wood nematode (PWN), *Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle (Nematoda: Aphelenchoididae), originating from North America, causes the destructive pine wilt disease. Pine wilt disease was first found in Nanjing, China in 1982, and has since become one of the most destructive forest calamities. In the last 20 years, PWN has spread to 10 provinces of Jiangsu, Zhejiang, Anhui, Guangdong, Shandong, Hubei, Jiangxi, Hunan, Chongqing, and Guizhou. The direct and indirect economic loss caused by the pine wood nematode is estimated to be approximately above a hundred billion, which has posed a strong threat to our pine resources, natural landscape and eco-environment (Sun, 1982; Cheng et al., 1983; Zhang and Luo, 2003).

Resistance is the ability of an ecosystem to counteract outside disturbance, and resilience is the ability of the system to recover to its initial status after disturbance. The above concepts quantitatively describe the anti-disturbance ability of the system (Holling, 1973; Ma, 1990). The resistance to PWN varied among different pine ecosystems, and after the invasion of PWN, the resilience and restoring direction of different pine ecosystems also differed. Describing the factors that affect ecosystem's response to PWN disturbance and the relationship among the elements have attracted the attention of researchers.

If we want to know the relationship among the elements in the system and understand the system structure, the structural model of the system should be first established. The structural model as a format of describing the system is between the mathematical model and literal model (in other words, literally expressed logistic analysis). Thus, the structural model can be used to deal with problems of a composite ecosystem; that is, it can deal macroscopically or microcosmic, qualitative or quantitative, concrete or abstract puzzles. Because the structural model has such characteristics, in the analysis of complicated systems we can often grasp the essence of problems, and find out the effective countermeasure.

There are many structural models that can be applied, of which the interpretative structural mode (ISM) is the most popular one. The ISM was developed in 1973 by Professor Huafert in the USA for analyzing some complicated socio-ecosystem problems. This model decomposes the complicated system into many subsystems (elements), and constructs a multistage hierarchical structural model with the aid of people's experience and knowledge and computers.

Generally, the working procedure of ISM includes the following: 1) create a question to define the analysis objective of ISM; 2) select the elements which constitute the system; 3) conceive the model to establish the adjacency and reachability matrix; 4) decompound the reachability matrix and set up the structural model; 5) create the interpretative structural model based on the structural model (Wang, 1998). ISM is a conceptual model, which can transfer ambiguous ideas and thoughts into intuitional ones with a good structural connection (Sun and Yin, 2001). It is very useful in analyzing systems with numerous variants, complicated relationship and unclear structure, and can also be applied in the ranking of schemes.

At present, the ISM is applied mostly in medicinal and economic fields (Paul, 1990; Kenneth, 1997; Zhang and Xie, 2002). So far, it has never been used in researches of disasters caused by biological invasion in the agricultural and forestry fields. The characteristics of ISM make it appropriate to analyze the responses of pine forest ecosystems to the PWN disturbance. Thus, we studied the multistage hierarchically structural model for the response of pine forest ecosystems to disturbance by alien invasive pests, so as to provide a basis to quantitatively analyze involved impact factors in the future.

2 Research methods

2.1 Field investigation

In August and October of 2003, based on the most consistent principle of site conditions and environmental factors, we set 11 sample plots of 30 m×30 m in Fuyang and Zhoushan cities, Zhejiang Province. Masson pines in the plots all originated from afforestation in the late 1960s and early 1970s. Except for the control plot, other plots were treated by removal measures in 1997 after the PWN attack in 1996.

To obtain data from the arbor, shrub and herbage, we used the fundamental methods of investigating each individual tree and the quadrat method. According to the sampling plots of 5 m×5 m, the diameter at breast height (DBH) (including basal diameter of stump), height and crown width of the trees were measured, and the name of each tree species was individually labeled. For every plot, 25 sampling subplots of shrub and herbage with 2 m×2 m size were investigated, and the indices of species, number, cover degree, average height and growth status, and the environmental factors of geographical position, elevation, gradient and slope direction were recorded.

2.2 Establishment of the adjacency matrix and conceptual model

Based on the investigation data collected in field sampling, an expert group was established which is made up by ten experts involving forestry protection, botany, ecology, and so on. The expert group thought that after the invasion and damage of PWN, the main factors that affected the responses of pine forestry ecosystems to the PWN disturbance were: 1) anthropogenic factors like prevention technology and its level; 2) damage degree of vector insect of *M. alternatus*; 3) species distribution pattern of pine forest; 4) soil; 5) meteorological factors; 6) biological characteristics of the pine trees including growth and regeneration; 7) biological characteristics of the second and jointly dominant species including growth and regeneration; 8) affecting factor in the removal of attacked trees; 9) affecting factor of other treatment measures (except for the removal measure); 10) surrounding pine mother trees; 11) topographical factors; 12) geographical location; 13) hydrological factors; 14) resistance (the ability of the system to resists the environment); and 15) resilience (the ability of the system to restore to its original status after a disturbance).

We used S_i to represent all the above factors, and S_{16} represents the response of pine forest ecosystems to PWN invasion, and all of the impact factors and their interrelationship were defined by experience of the experts after discussion (The Forestry Department of Anhui Agricultural College, 1980).

Thus, the conceptual model for the response of the pine forestry ecosystem to the disturbance of PWN has been obtained: $S_1\mathrm{R}S_8$, $S_1\mathrm{R}S_9$, $S_2\mathrm{R}S_3$, $S_2\mathrm{R}S_{14}$, $S_3\mathrm{R}S_2$, $S_3\mathrm{R}S_{10}$, $S_3\mathrm{R}S_{13}$, $S_3\mathrm{R}S_{14}$, $S_3\mathrm{R}S_{15}$, $S_4\mathrm{R}S_3$, $S_4\mathrm{R}S_6$, $S_4\mathrm{R}S_7$, $S_4\mathrm{R}S_{10}$, $S_4\mathrm{R}S_{15}$, $S_5\mathrm{R}S_2$, $S_5\mathrm{R}S_3$, $S_5\mathrm{R}S_4$, $S_5\mathrm{R}S_6$, $S_5\mathrm{R}S_7$, $S_5\mathrm{R}S_{10}$, $S_5\mathrm{R}S_{13}$, $S_5\mathrm{R}S_{15}$, $S_6\mathrm{R}S_2$, $S_6\mathrm{R}S_{13}$, $S_6\mathrm{R}S_{14}$, $S_6\mathrm{R}S_{15}$, $S_7\mathrm{R}S_{13}$, $S_7\mathrm{R}S_{15}$, $S_8\mathrm{R}S_2$, $S_8\mathrm{R}S_3$, $S_8\mathrm{R}S_{14}$, $S_8\mathrm{R}S_{15}$, $S_9\mathrm{R}S_2$, $S_9\mathrm{R}S_3$, $S_9\mathrm{R}S_{10}$, $S_9\mathrm{R}S_{14}$, $S_9\mathrm{R}S_{15}$, $S_{10}\mathrm{R}S_2$, $S_{10}\mathrm{R}S_3$, $S_{10}\mathrm{R}S_{13}$, $S_{10}\mathrm{R}S_{15}$, $S_{11}\mathrm{R}S_2$, $S_{11}\mathrm{R}S_3$, $S_{11}\mathrm{R}S_4$, $S_{11}\mathrm{R}S_5$, $S_{11}\mathrm{R}S_{10}$, $S_{11}\mathrm{R}S_{13}$, $S_{11}\mathrm{R}S_{15}$, $S_{12}\mathrm{R}S_2$, $S_{12}\mathrm{R}S_3$, $S_{12}\mathrm{R}S_4$, $S_{12}\mathrm{R}S_5$, $S_{12}\mathrm{R}S_{10}$, $S_{12}\mathrm{R}S_{13}$, $S_{12}\mathrm{R}S_{15}$, $S_{13}\mathrm{R}S_2$, $S_{13}\mathrm{R}S_3$, $S_{13}\mathrm{R}S_{10}$, $S_{13}\mathrm{R}S_{15}$, $S_{14}\mathrm{R}S_{16}$, $S_{15}\mathrm{R}S_{16}$, in which, S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16} are nodes (Fig. 1).

Based on the above model, the connection matrix with 16 stages can be obtained: $\boldsymbol{A}=[a_{ij}]_{16\times16}$, $a_{ij}=\left\{\begin{matrix}1, S_i\mathrm{R}S_j\\0, S_i\mathrm{R}S_j\end{matrix}\right\}$, where $S_i\mathrm{R}S_j$ means that S_i, can cause S_j. We then established the adjacency matrix $\boldsymbol{A}$.

$$
\boldsymbol{A} = \begin{bmatrix}
0&0&0&0&0&0&0&1&1&0&0&0&0&0&0&0\\
0&0&1&0&0&0&0&0&0&0&0&0&0&1&0&0\\
0&1&0&0&0&0&0&0&0&1&0&0&1&1&1&0\\
0&0&1&0&0&1&1&0&0&1&0&0&0&0&1&0\\
0&1&1&1&0&1&1&0&0&1&0&0&1&0&1&0\\
0&1&0&0&0&0&0&0&0&0&0&0&1&1&1&0\\
0&0&0&0&0&0&0&0&0&0&0&0&1&0&1&0\\
0&1&1&0&0&0&0&0&0&0&0&0&0&1&1&0\\
0&1&1&0&0&0&0&0&0&1&0&0&0&1&1&0\\
0&1&1&0&0&0&0&0&0&0&0&0&1&0&1&0\\
0&1&1&1&1&0&0&0&0&1&0&0&1&0&1&0\\
0&1&1&1&1&0&0&0&0&1&0&0&1&0&1&0\\
0&0&1&1&0&0&0&0&0&1&0&0&0&0&1&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0
\end{bmatrix}
$$

2.3 Establishment of the reachability matrix

By computing the square value of $(\boldsymbol{A}+\boldsymbol{I})$ with Matlab 6.5 software according to the operation rule of Buer algebra (namely $0+0=0$, $0+1=1$, $1+0=1$, $1+1=1$, $0\times0=0$, $0\times1=0$, $1\times0=0$, $1\times1=1$), and via computation by a computer we obtain:

$$
(\boldsymbol{A}+\boldsymbol{I})^5 = (\boldsymbol{A}+\boldsymbol{I})^6 = \begin{bmatrix}
1&1&1&1&0&1&1&1&1&1&0&0&1&1&1&1\\
0&1&1&1&0&1&1&0&0&1&0&0&1&1&1&1\\
0&1&1&1&0&1&1&0&0&1&0&0&1&1&1&1\\
0&1&1&1&0&1&1&0&0&1&0&0&1&1&1&1\\
0&1&1&1&1&1&1&0&0&1&0&0&1&1&1&1\\
0&1&1&1&0&1&1&0&0&1&0&0&1&1&1&1\\
0&1&1&1&0&1&1&0&0&1&0&0&1&1&1&1\\
0&1&1&1&0&1&1&1&0&1&0&0&1&1&1&1\\
0&1&1&1&0&1&1&0&1&1&0&0&1&1&1&1\\
0&1&1&1&0&1&1&0&0&1&0&0&1&1&1&1\\
0&1&1&1&1&1&1&0&0&1&1&0&1&1&1&1\\
0&1&1&1&1&1&1&0&0&1&0&1&1&1&1&1\\
0&1&1&1&0&1&1&0&0&1&0&0&1&1&1&1\\
0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&1\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&1\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1
\end{bmatrix}
$$

It is reachability matrix $\boldsymbol{R}$.

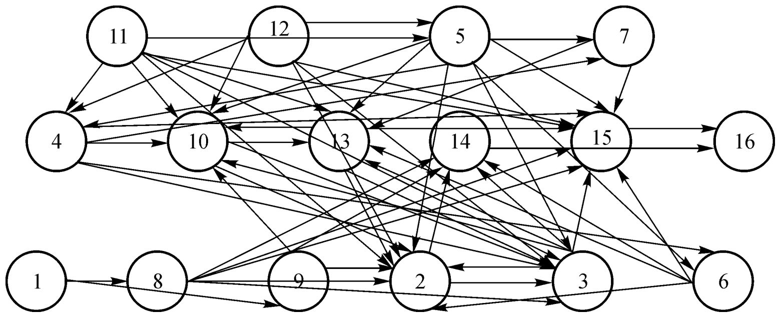

Fig. 1 The conceptive model of response factors

2.4 Section and decomposition within the stages

We make Table 1 represent the reachable and antecedent set of each element in the reachability matrix which affects the response of the pine forestry ecosystem to the disturbance of PWN. The column $R(n_i)$ represents the reachable set, the column $A(n_i)$ represents the antecedent set.

From Table 1, we can see: $A(n_1)=R(n_1)\cap A(n_1)$, $A(n_{11})=R(n_{11})\cap A(n_{11})$, $A(n_{12})=R(n_{12})\cap A(n_{12})$, thus, the conjunct set is $T=\{1, 11, 12\}$. Because $R(1)\cap R(11)\cap R(12)=\{2, 3, 4, 6, 7, 10, 13, 14, 15, 16\}$ is not empty, so all of the elements belong to the same connected domain, and the bottom elements are S_1, S_{11} and S_{12}.

According to the condition of $R(n_i)=R(n_i)\cap A(n_i)$ which forms the strong connectivity field, we know that only the 16th element in all of the elements of reachability matrix that affects the response of the pine forestry ecosystem to the disturbance of PWN meets this item. Consequently, element S_{16} is a tiptop stage element. Ruling out the 16th row and column of the reachability matrix which is second class partition, we can get the 2nd elements of S_{14}, S_{15}. Accordingly, the 3rd elements of S_2, S_3, S_4, S_6, S_7, S_{10}, S_{13}, the 4th elements of S_5, S_8, S_9 and the 5th elements of S_1, S_{11}, S_{12}. Based on the above analysis, the multistage hierarchical structural model for the response of the pine forest ecosystem to PWN disturbance can be obtained, namely, the interpretative structural model for the response of the pine forests ecosystem to PWN disturbance (Fig. 2).

3 Results and analysis

From Fig. 2, we can see that the system which affected the response of the pine forest ecosystem to PWN disturbance is a five-degree multistage hierarchical system, in which direct affecting factors are resistance and resilience. Obviously, the higher the resistance and resilience of the pine forest system, the more timely the response made by the ecosystem to PWN's invasion and the less infection on the pine ecosystem.

Table 1 Elements structure of ISM

element	$R(n_i)$	$A(n_i)$	$R(n_i)\cap A(n_i)$
1	1, 2, 3, 4, 6, 7, 8, 9, 10, 13, 14, 15, 16	1	1
2	2, 3, 4, 6, 7, 10, 13, 14, 15, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	2, 3, 4, 6, 7, 10, 13
3	2, 3, 4, 6, 7, 10, 13, 14, 15, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	2, 3, 4, 6, 7, 10, 13
4	2, 3, 4, 6, 7, 10, 13, 14, 15, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	2, 3, 4, 6, 7, 10, 13
5	2, 3, 4, 5, 6, 7, 10, 13, 14, 15, 16	5, 11, 12	5
6	2, 3, 4, 6, 7, 10, 13, 14, 15, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	2, 3, 4, 6, 7, 10, 13
7	2, 3, 4, 6, 7, 10, 13, 14, 15, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	2, 3, 4, 6, 7, 10, 13
8	2, 3, 4, 6, 7, 8, 10, 13, 14, 15, 16	1, 8	8
9	2, 3, 4, 6, 7, 9, 10, 13, 14, 15, 16	1, 9	9
10	2, 3, 4, 6, 7, 10, 13, 14, 15, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	2, 3, 4, 6, 7, 10, 13
11	2, 3, 4, 5, 6, 7, 10, 11, 13, 14, 15, 16	11	11
12	2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 15, 16	12	12
13	2, 3, 4, 6, 7, 10, 13, 14, 15, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13	2, 3, 4, 6, 7, 10, 13
14	14, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	14
15	15, 16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15	15
16	16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	16

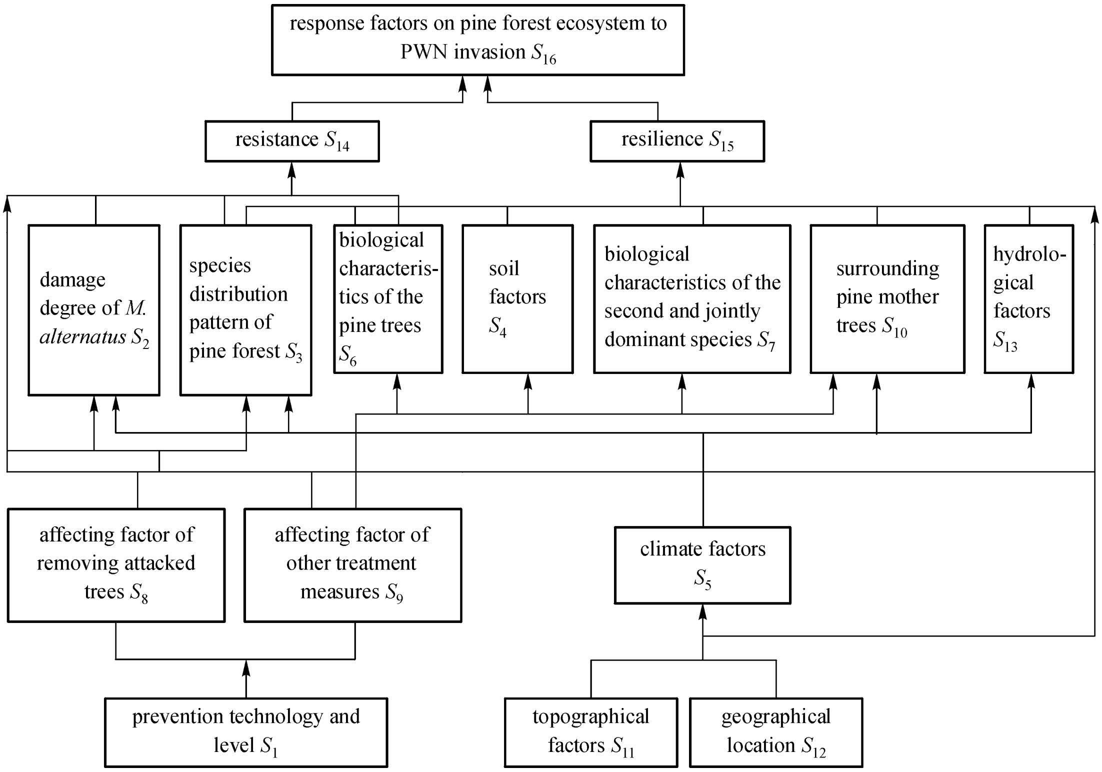

Fig. 2 The interpretative structural model for the response factors on pine forest ecosystem to PWN disturbance

Furthermore, the analyses to the 2nd, 3rd and 4th degree factors showed that the direct factors that affected the resistance of the pine forest ecosystem are the damage degree of vector insects, distribution pattern of plant species and ecological features of pines. As for resilience, it was influenced directly by distribution pattern of plant species and ecological features of pines, soil factor, biological characteristics of the second and jointly dominant species, surrounding species mother trees and hydrological factors. Among them, the controllable factor is distribution pattern of plant species in the pine forest, and it can have considerable effects on the resistance and resilience. As for the damage degree of vector insect which directly affects the resistance, it can be controlled through removing attacked trees and other treatment measures. If the measure of removing attacked trees is taken timely and thoroughly, with the assistance of other proper treatment measures such as suffocation, pesticide, etc. after the invasion of PWN, the resistance of the pine forest system would be increased and vice versa. Consequently, not only the distribution pattern of plant species and ecological features of pines affected the resistance of the pine forest ecosystem; the factor of removing attacked trees and other treatment measures also influenced the resistance via affecting the damage degree of *M. alternatus* and distribution pattern of plant species indirectly.

More factors affect the resilience except for factors of soil, hydrology, surrounding pine mother trees and biological characteristics of the second and jointly dominant species, and the climate factors can also have a direct or indirect influence by affecting the above factors on the resilience of the system. Thus, the restoration course will vary with the different environmental conditions.

As for the relationship between the 4th and 5th elements, among 5th elements, the topographical factors and geographical location will affect the climate factor, while removal and other control measures will be influenced by the anthropogenic factors like prevention technology and its level. Generally, the topographical factors like elevation, gradient and slope direction, diversity of geographical location and improvement of prevention technology level all influenced the response of the pine forest ecosystem to PWN disturbance (Qin et al., 2003).

4 Conclusions

Based on results of ISM, in order to make the pine forest ecosystem respond positively and timely to PWN's invasion, the paper made the following recommendations:

1) Select the anti-pest tree species, arrange the plant species properly, and optimize the distribution pattern of plant species.

2) Closely monitor population density and management of *M. alternatus* vector in the forest. Remove the attacked trees timely and rationally with the assistance of other control measures.

3) The original biodiversity surrounding the pine forest

system must be preserved, which will ensure the preservation of the gene pool and germplasm resources of the pine trees.

4) Regular and systematical monitoring, forecast and quarantine on *B. xylophilus* invasion will help better monitor forest trees and save the trees from further infestation.

5) The achieved information about PWN and the vector and their management should be broadcasted through mass media to foresters, the public and researchers. It will also help get feedback from them for developing better management strategies of PWN and its vector (Sun and Yin, 2001; Qin et al., 2003).

The paper only analyzed the structural model for the response of the pine forest ecosystem to PWN disturbance, and we will further study its quantitative part after we get the related data of the natural enemy of *M. alternatus*. By establishing the ISM model, we only found the key factors affecting resistance and resilience of the pine forest ecosystem under certain conditions. We will continue the study of the relationship among the key factors to provide a theoretical basis for the evaluation criterion and indicator system of the resistance and resilience ability of pine forest ecosystems to PWN's invasion.

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