松材线虫(*Bursaphelenchus xylophilus*)入侵对马尾松(*Pinus massoniana*)林分生长的影响及相关生长模型

石 娟[1], 骆有庆[1,*], 武海卫[1], Kari Heliövaara[2], 梁丽壮[1]

(1. 北京林业大学省部共建森林培育与保护教育部重点实验室 北京 100083;
2. 赫尔辛基大学应用生物与森林动物系, 赫尔辛基(芬兰) FIN-00014)

摘要:松材线虫(*Bursaphelenchus xylophilus*)是一种松树上发生严重的有害生物,它不仅改变了生态系统的结构和功能,而且改变了系统内生物的原有特性和地理分布。松材线虫及其引起的松树萎蔫病已对中国马尾松林(*Pinus massoniana*)的树木成长产生了巨大影响。基于此,使用"每木调查法"和"样方法",对松材线虫入侵后的马尾松林内松树的各项生长指标因子进行了调查分析,其结果表明:自松材线虫 1996 年入侵所调查地区的松林后,对于受害松树不管是伐倒木(被伐倒)还是倒木(自然倒地),其对周围马尾松胸径生长的影响是显著的,而对树高生长的影响不显著。最后建立了一系列的灰色和灰色-马尔可夫链数学模型,其预测结果精度高,可用于今后受害和未受害区马尾松林分因子的生长预测。

关键词:松材线虫(*Bursaphelenchus xylophilus*);干扰;生长模型;灰色预测;灰色-马尔可夫组合模型
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Impact on forest growth and related growth models of the *Pinus massoniana* population invaded by *Bursaphelenchus xylophilus*

SHI Juan[1], LUO You-Qing[1,*], WU Hai-Wei[1], Kari Heliövaara[2], LIANG Li-Zhuang[1]

1 *The Key Laboratory for Silviculture and Conservation of Ministry of Education, Forestry College, Beijing Forestry University, P. O. Box* 113, *Beijing* 100083, *China*

2 *Department of Applied Biology, Forest Zoology, University of Helsinki, FIN*-00014 *Helsinki, Finland*

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Abstract: *Bursaphelenchus xylophilus* (Pine wood nematode, PWN) is a serious pest of pines that changes the original biological and geographical distribution as well as the structure and function of the natural ecosystems. The nematode and the associated pine wilt disease have a great impact on the stand growth of Masson pine forests in China. The growth rule of individual forest factors after the PWN invasion was analyzed using of "the technique of censusing every individual" and "quadrat method". The results showed that the invasion of PWN in 1996 had a significant impact on the diameter growth of the pines, but PWN only seldom affected the height growth of the pines. Based on this, the paper also established the grey

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作者简介:石娟(1979 ~),山西人,博士,主要从事林业外来有害生物研究. E-mail:shi_juan@263.net

* 通讯作者 Correspongding author. E-mail: youqingluo@126.com

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Biography: SHI Juan, Ph. D., mainly engaged in forest invasive alien species. E-mail: shi_juan@263.net

forecast and grey-Markov combination models of the Masson pine's growth attacked by PWN. This series of models had a high simulation accuracy and could be applied to the prediction for stand description factors in Masson pine forest, no matter whether it was attacked by PWN or not.

Key Words: pine wood nematode (PWN) (*Bursaphelenchus xylophilus*); disturbance; growth model; grey forecast; model combination of grey-Markov

The pine wood nematode (PWN), *Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle (Nematoda: Aphelenchoididae), originating from the North America, causes the destructive pine wilt disease[1,2]. Although indigenous in North America, the PWN has been reported from Japan[3], Korea and China[4,5] in Asia, and Portugal in Europe[6,7]. The nematode causing pine wilt disease has thus become a worldwide quarantine pest.

In China, the direct economic loss caused by the PWN is estimated at approximately RMB 2.5 billion with indirect economic loss exceeding RMB 25 billion[8,9]. The Japanese pine sawyer beetle (PSB), *Monochamus alternatus* Hope (Coleoptera: Cerambycidae) is the most important vector for the transmission of the pine wood nematode in Japan and China. The beetle has been recorded on more than 15 species of *Pinus*, plus several species of *Abies*, *Cedrus*, *Picea*, and *Larix*[10,11]. Masson pine, *Pinus massoniana*, an indigenous species found in 19 southern provinces of China, has suffered from 40% to 50% tree mortality in southern China[12–15].

For controlling the crisis of the wilt disease, the main measures taken in China were cutting down the invaded trees and using chemical control against the nematode. However, because of the difficulty in practical operation, some infected, weakened and feeble Masson pines were left standing. Finally, these trees died and fell down before they were removed[16]. Consequently, both stumps of the felled trees and fallen dead trees were left in the stand. There are two disturbance ways in Masson pine forest invaded by PWN in China: natural disturbance caused by the fallen trees, and human disturbance caused by the stumps.

Many models of stem height and diameter growth in plants have been developed, which are formulated within the framework of an existing tree plantation growth model[17,18], The occurrence period and extent of plant diseases and insect pests can be predicted by using, for instance, the grey system model which needs less data than many other models[19–22]. Markov models are matrices of transition probabilities between states and are used to project a vector of state distribution forward in time[23–27]. However, every model also has their shortcomings. For which, in the future, forest models should combine the predictive power and flexibility of process-based models with the empirical information and descriptive accuracy of conventional mensuration-based models[28, 29].

Although some studies have been conducted on the morphology and biology of the Japanese pine sawyer and the nematode[30–35], the research on impact of PWN on growth of Masson pine and the growth model of pine forest after the invasion of PWN is still lacking. The objective of this study was to investigate how the disturbance of PWN (natural and human disturbance) affects the growth of remaining unattacked Masson pines and build growth models for the stand after the invasion of PWN. Once these models are established, a solid foundation for a further explanation of the impact mechanism of PWN to pine forest ecosystems will be created, and it will also give an example on how to study the impact on forest growth and forecast that from the view of insect pests and diseases.

1 Material and methods

1.1 Field site and sampling procedure

The study site was located in Fuyang City, Zhejiang Province which is situated at the east part of China. Fuyang City comprises of 17 towns and 8 counties, with an area of 1830 km^2 (29°44′—30°12′N, 119°25′—120°09′E).

The area has a subtropical monsoon climate. The mean annual precipitation is about 1000 mm and mean annual temperature 16°C in the area[36].

We selected two uniform Masson pine experimental plots (30m × 30m) in Fuyang county. Plot 1 is located on He Jiamen Mountain in Dongshan village (30°04′51.4″N, 119°57′5.1″E) at an altitude of 98 m above sea level (a. s. l.). The pines of Plot 1 are heavily attacked by the wilt disease. In 2004 (the investigating year), the trees were about 25 years old, and the stand density was 2533 trees per hectare. Dominant species in the shrub layer include *Phyllostachys nidularia*, *Loropetalum chinensies* and *Eurya hebeclados*. The presence of PWN in the dead pine trees was verified by the Baermann funnel method[37].

Plot 2 (Check) is located in Shimu village (30 08′20.5″N, 119°55′44.2″E). The pines of Plot 2 have remained unattacked by the pine wilt disease. In 2004 the trees were about 27 years old with the stand density of 2622 trees per hectare and located at an altitude of 131 m (a. s. l.). Dominant species in the shrub layer include *Pistacia chinensis* and *Loropetalum chinensies*.

We use the technique of censusing every individual tree in the two plots to obtain data from the attacked trees. The diameter in breast height (including basal diameter of stump), height and crown width of the trees were measured, and each tree was individually labeled in 2004[38-40].

Individual trees were subjected to stem analyses in June 2004 in order to investigate how the disturbance of PWN affects the growth of remaining unattacked Masson pines. Three healthy-looking trees around the stump were measured in Plot 1, the mean value (symbol S in figures) representing the effects of human disturbance on the stand. Also three healthy-looking trees around fallen dead trees were measured in Plot 1, the mean value (F) representing the effects of natural disturbance of the stand. In addition, one tree representing the mean trees was measured in Plot 1 (M1) and Plot 2 (M2) respectively. In total, seven trees were analyzed in Plot 1, and one tree was analyzed in Plot 2. Theses trees represented Masson pines which are affected by PWN to the different disturbance degrees[41].

1.2 Grey system model

The grey system theory, established by Deng[42], advanced a method of dealing with the grey knowledge according to the measured correlation coefficients. The grey system proposes the approach of "generation" in data processing, that is, through "generation" make the disordered data sequence randomly attenuate and thus changing into relatively ordered data sequence[22]. The objective of the present study was to predict the growth process of forest factors of Masson pine forest after the invasion of PWN using the present model.

If $X^{(0)}$ is non-negative sequence:

$$X^{(0)} = (x^{(0)}(1), x^{(0)}(2), \cdots, x^{(0)}(n)) \tag{1}$$

Where $x^{(0)}(k) \geqslant 0, k = 1, 2, \cdots, n$; $X^{(1)}$ is the accumulating generation sequence of $X^{(0)}$ once(1-AGO):

$$X^{(1)} = (x^{(1)}(1), x^{(1)}(2), \cdots, x^{(1)}(n)) \tag{2}$$

In which,

$$x^{(1)}(k) = \sum_{i=1}^{k}, k = 1, 2, \cdots, n \tag{3}$$

The common model of grey system theory is GM (1,1) representing first linear differentiable equations of single sequence and given by:

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = u \tag{4}$$

The solution form of formula (4) is:

$$\begin{cases} x^{(1)}(0) = x^{(0)}(1) \\ x^{(1)}(t) = \left(x^{(0)}(1) - \frac{u}{a}\right)e^{-a(t-1)} + \frac{u}{a} \end{cases} \tag{5}$$

In the formula, a, and u are the pending parameters; If $\hat{a}$ is parameter column, then the parameter column of least squares estimator of GM(1,1) is computed by:

$$\hat{a} = \begin{bmatrix} a \\ u \end{bmatrix} = (B^T B)^{-1} B^T Y \tag{6}$$

In which:

$$Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \bullet \\ \bullet \\ \bullet \\ x^{(0)}(n) \end{bmatrix}, \quad B = \begin{bmatrix} -\frac{1}{2}[x^{(1)}(2) + x^{(1)}(1)], 1 \\ -\frac{1}{2}[x^{(1)}(3) + x^{(1)}(2)], 1 \\ \bullet \\ \bullet \\ \bullet \\ -\frac{1}{2}[x^{(1)}(n) + x^{(1)}(n-1)], 1 \end{bmatrix}$$

To test the predictive precision, we use post-test residue ratio C and minimum error probability P to calculate:

$$C = \frac{S_2}{S_1} \tag{7}$$

$$P = p\{\,|q(k) - \bar{q}| < 0.6745S1\,\},\ k = 1, 2, \cdots, n \tag{8}$$

In the formula, S_1^2 and S_2^2 are the variance of $x^{(0)}(k)$ and $q(k)$, respectively, and the calculating formulas are:

$$S_1^2 = \frac{1}{n}\sum_{k=1}^{n}(x^{(0)}(k) - \bar{x})^2, \bar{x} = \frac{1}{n}\sum_{k=1}^{n}x^{(0)}(k) \tag{9}$$

$$S_2^2 = \frac{1}{n-1}\sum_{k=2}^{n}(q(k) - \bar{q})^2, \bar{q} = \frac{1}{n-1}\sum_{k=2}^{n}q(k) \tag{10}$$

Where $q(k)$ is the residual calculated by using the following formula:

$$q(k) = x^{(0)}(k) - \hat{x}^{(0)}(k) \tag{11}$$

Note: the data with "∧" represents the calculating value by models. For example: according to Formula 5, the predicted values of $\hat{x}^{(1)}(k-1)$ and $\hat{x}^{(1)}(k)$ can be calculated by models, then, the restored value or tendency value of $\hat{x}^{(0)}(k)$ is computed by the following formula:

$$\hat{x}^{(0)}(k) = \hat{x}^{(1)}(k) - \hat{x}^{(1)}(k-1) \tag{12}$$

1.3 Model combination of grey-markov

Yang *et al.* applied the grey system theory of chlorophyll degradation in *Chamaecyparis* needle-leaf in Taiwan. Four grey prediction models were established and compared with the results of linear and exponential regression analysis. The residual error and accuracy range showed that the grey prediction process is much better than a regression analysis[43]. However, Chen and Lee thought the original grey prediction model used a mathematical hypothesis, and approximation to transform a continuous differential equation into a discrete one has some shortcoming[44].

Since the grey-markov model combines the advantages of GM(1,1) long-term prediction and Markov matrix of state transitional probability, it is more suitable for the long-term prediction, especially for the short-term prediction of data sequence which fluctuate randomly to a large degree. Its forecasting precision is fairly high[42, 45], and the prediction precision is better than only using the grey model[46-48].

The model combination of grey-markov includes the following steps, using "S" (the healthy Masson pine around the stump) as an example:

1.3.1 Building GM(1.1) model

The model based on the basic information of current annual increment in *DBH* of "S" Masson pines from 1983 to 2003, is the same as the above GM(1.1) model. Then, using the model to calculate the forecasting value, let $\hat{x}^{(1)}(t)$ represent the forecasting value of the model in t year.

According to Formula 12, the restored value of model—$\hat{x}^{(0)}(t)$ can be calculated, the relative growth value in each year (marked with $W(t)$) is also defined by using the percentage of the actual growth value and $\hat{x}^{(0)}(t)$. Then:

$$W(t) = \frac{x^{(0)}(t)}{\hat{x}^{(0)}(t)} \times 100 \qquad (13)$$

1.3.2 The division of State

There are some differences between restored (or tendency) and actual values. The difference is random value which represents the variation of system state. If the difference of actual and restored values is a random value, then all of the ratio of random values and restored values can be considered as a state set. According to the actual situation, the state set can be divided some intervals, each interval is corresponding with one state. If the ratio of the random and the restored values of a original data belongs to the $E_i = [A_i, B_i]$, then we call present state of the random value of system is E_i.

In this paper, the state was divided by using the relative growth value $W(t)$ ($t = 1, 2, \cdots, 21$) as the forecasting subject of Markov chain. According to the local historical data and field investigations, the standards of dividing state were obtained.

1.3.3 The state defining of the current annual increment in *DBH* on the time series

According to the standards of dividing state, the annual state of the current annual increment in *DBH* was converted from 1983 to 2003.

1.3.4 The formation of the matrix of state transitional probability

According to the formula $P_{ij}(m) = \frac{m_{ij}(m)}{M_i}$, we can build the matrix of state transitional probability in each step —$R(m)$.

In the formula, $P_{ij}(m)$ represents the transitional probability from state i to state j through m steps; $m_{ij}(m)$ represents the transitional times from state i to state j through m steps; M_i represents the times of occurrence of state i.

1.3.5 Prediction of the state of current annual increment in *DBH* of "S" in 2004 by using Markov chain

According to the row vector of $R(1) - R(m)$ in the matrix of state transitional probability corresponding to the original state value respectively in 1999 — 2003, we can form a new matrix of probability, then sum up the column vectors in the new matrix of transitional probability. The state corresponding to the biggest figure is just the state of future development of the system, that is, the forecasting state $w(t)$.

1.3.6 The defining of the forecasting value and its extent in 2004

All the above outcome is relative product (also the grey product), and should be restored according to the tendency rules of Formula 13. Thus the forecasting value ($t = 22$) using the grey-markov combination model is:

$$\frac{W(22)}{100} \times \hat{x}^{(0)}(22) \qquad (14)$$

Finally, the forecasting value and its extent of "S" in 2004 will be predicted.

1.3.7 Forecasting effect checking of model combination of grey-markov

According to the above analysis, we can use the predictive accuracy (the ratio of the forecasting current annual increment in *DBH* and the actual growth value of "S" in 2004) to calculate the fitting precision of grey-Markov combination model.

1.3.8 Forecasting effect checking of GM(1.1) and grey-markov combination model

The following formula was used to check the results of GM (1,1) and forecasting model combination of grey-markov.

relative error
$$\Delta k = \frac{|q(k)|}{x^{(0)}(k)} \quad (15)$$

2 Results

2.1 Influence of PWN on the diameter growth of the stand

First, we made the variance analysis and the multiple comparisons of total increment in *DBH* of Masson pines affected by PWN in different degree. The variance analysis shows that after the PWN attacked the Masson pine forest in 1996. No matter in which way the pines fell to the ground (naturally or by cutting), the influence on the *DBH* growth of the remaining trees around was significant ($F = 6.237$, $P < 0.01$, $df = 3, 103$, Fig. 1).

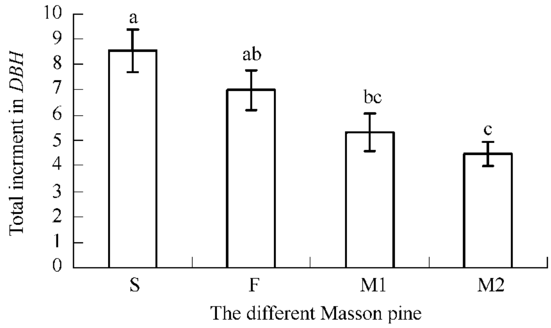

Fig. 1 The Multiple Comparisons of Total Increment in *DBH* of Masson Pines Affected by PWN

S: Healthy pine near the stump; F: Healthy pine near fallen dead trees; M1: Mean growth of the trees in the attacked Plot 1; M2: Mean growth of the trees in the unattacked Plot 2

Note: Means within rows followed by the same letter are not significantly different. The mean difference is significant at the 0.05 level

Then, we made the impact curves of current annual and mean increment in *DBH* of Masson pines invaded by PWN (Fig. 2). Before 1993, the current annual increments in *DBH* of the studied trees were basically the same, but after 1993 the increment tendency changed. The slowest diameter growth of "S" (trees around stump) occurred in 1996, and the fastest diameter growth occurred in 1999. Also the slowest growth of "F" (trees around dead, fallen trees) and mean tree's diameters in Plot 1 occurred in 1996, but the peak occurred in 1997. The first peak of the mean tree's diameter growth in Plot 2 occurred in 1996, when the slowest growth rates were observed in the invaded Plot 1.

After the invaded trees were removed in 1997, the changing tendency of the growth increments of mean trees in Plot 1 and 2 began to be the same. This indicates that the pathogen had already been under control, and the stand mean increment in *DBH* started to increase. The "S" and "F" trees growing close to the attacked trees were not damaged and reached a small peak in diameter growth in 1999 and 1997, respectively. Their mean increments in *DBH* have declined in contrast with the situation before the damage. In addition, the total increment and mean increment in 1997 (the year in which the invaded trees were removed) can be arranged in the following orders (from high to low): (1) S, (2) F, (3) M1, (4) M2.

2.2 Influence of PWN on the height growth of the stand

Next we made the variance analysis of total height increment of Masson pines affected by PWN in different degrees. The variance analysis shows that after the PWN attacked the forest, no matter in which way the pines fell to the ground (naturally or by cutting), the influence on the height growth of the healthy Masson pines around was not significant ($F = 2.406$, NS, $df = 3, 99$).

Then, we calculated the impact curves of current annual and mean height increments of the pines invaded by PWN (Fig. 3). With regard to the current annual increment in height, the general tendencies of the height growth are basically the same. Only in 1996 when the PWN attacked, "S", "F" and the mean tree in Plot 1 (M1) showed a small abyss of growth, but they recovered in the following one or two years. However, in contrast with the trees in the unattacked Plot 2 (M2) in these years, they did not follow the above rule.

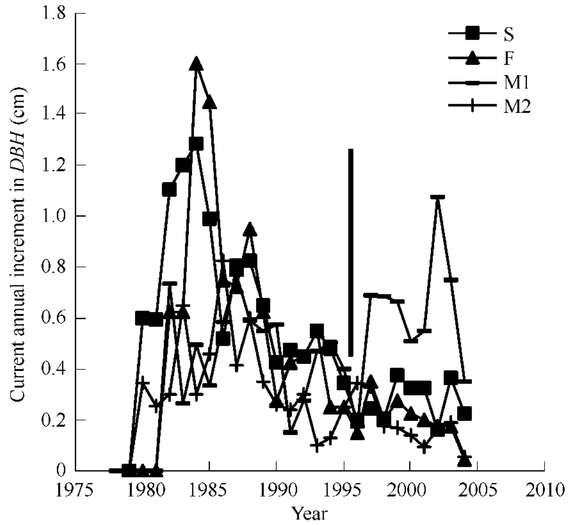

Fig. 2　Current annual increment in *DBH* of Masson pines

Vertical bar indicates the attacking year of the pine wood nematode

Symbols as in Fig. 1

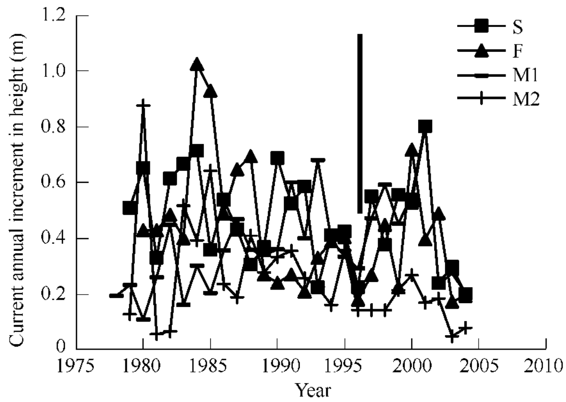

Fig. 3　Current annual increment in the height of Masson pines

Vertical bar indicates the attacking year of the pine wood nematode

Symbols as in Fig. 1

The height growth of "F" and "S" reached the peak in 1998 and 1997 after reduced growth in 1996. The peak of height growth of "F" is one year later than that of "S". One plausible explanation is that removing the invaded trees can quickly alleviate the pressure of competition in space and sunshine among the remaining pines resulting in the maximum height growth volume. In contrast, competition of nutrients among the pines around the fallen dead trees was alleviated, but competition in space still exists during a certain period of time. Thus the height growth increase caused by the fallen dead trees takes place one or two years later (this period of time is just the time needed by the invaded trees turning into fallen dead wood).

However, our research also shows that the mean height increment in 1997 of the mean tree in Plot 1 is higher than that in Plot 2. Thus, after removing the invaded pines, the annual mean increments of the remaining Masson pines generally increased.

2.3　Grey forecasting model of Masson pine growth after the PWN invasion

According to the results above, the influence of PWN on the *DBH* growth of the healthy Masson pines around was significant, but the influence on the height was not. So we divided the current annual increments in *DBH* of "S", "F" and mean tree in Plot 1 into two parts, before and after 1996, and build GM (1,1) models of pine forest growth respectively. Table 1 shows the results of the analysis.

2.4　Forecasting effect checking of Grey forecasting model

The predictive precision of the built grey forecasting model is tested by using the post-test residue ratio C and minimum error probability P. The smaller C is, and the bigger P is, the better the result will be. According to the two parameters C and P for mean trees in Plot 1 (M1) and Plot 2 (M2), the simulation accuracy of Masson pine growth is good without the need to be rectified. As for "S" and "F", the simulation accuracy of pine height growth is good, but the simulation accuracy of *DBH* growth is slightly worse. With regard to this, we consider to rectify the result by using model combination of grey-markov. "S" is taken as an example to make the analysis[22].

Table 1 Grey forecasting model of the growth of Masson pines affected by PWN

Masson pine affected by PWN	Measurement	Grey model	C	P
S	*DBH*(before 1996)	$X^{(1)}(t+1) = -56.2551e^{-0.0212t} + 56.8501$	0.3941	1
	DBH(after 1996)	$X^{(1)}(t+1) = 1.0253e^{0.1871t} - 0.8253$	0.4071	1
	height	$X^{(1)}(t+1) = 3.0152e^{0.1270t} - 2.7092$	0.2857	1
F	*DBH*(before 1996)	$X^{(1)}(t+1) = 3.9903e^{0.1009t} - 3.7153$	0.1693	1
	DBH(after 1996)	$X^{(1)}(t+1) = 1.6510e^{0.1086t} - 1.5010$	0.3669	1
	height	$X^{(1)}(t+1) = 0.8099e^{0.2954t} - 0.6302$	0.2817	1
M1	*DBH*(before 1996)	$X^{(1)}(t+1) = 2.0701\ e^{0.1848t} - 1.8051$	0.2998	1
	DBH(after 1996)	$X^{(1)}(t+1) = -16.7793\ e^{-0.0412t} + 16.9543$	0.3115	1
	height	$X^{(1)}(t+1) = 1.1935e^{0.1909t} - 1.0321$	0.3287	1
M2	*DBH*	$X^{(1)}(t+1) = 0.6634e^{0.2360t} - 0.5634$	0.3424	1
	height	$X^{(1)}(t+1) = 0.4600e^{0.2438t} - 0.3171$	0.2280	1

S: Healthy pine around the stump; F: Healthy pine around fallen dead trees; M1: Mean growth of the trees in the attacked Plot 1; M2: Mean growth of the trees in the unattacked Plot 2

2.5 Model combination of grey-markov after the PWN invasion

According to the establishing steps of grey-Markov model, we got the standards of dividing states based on the local historical data and our investigation (Table 2), and the forecasting result of current annual increment in *DBH* of "S" in 2004 (Table 3).

Table 2 Rules of dividing states

State	Number	Relative growth value
Bumper shortfall years	1	≤89.15
Shortfall years	2	(89.15,99.15]
Average years	3	(99.15,109.15]
Harvest years	4	(109.15,119.15]
Bumper harvest years	5	>119.15

Table 4 shows that the biggest probability and its corresponding state 2 in the "Total" block can tell us the state in the forecasting year is 2. The product (grey) of state 2 has the extent of (89.15,99.15] in Table 3. We can find out the median, and the forecasting value is 94.15 that marked with $W(22)$, then all above were restored according to the tendency rules. That result is,

Table 3 Forecasting matrix table of current annual increment in *DBH* of the healthy pines near the stump (S) in 2004

Starting year	Starting state	Transitional steps	1	2	3	4	5
2003	2	1	0.5	0	0	0.166667	0.3333
2002	1	2	0	0.4	0	0.2	0.4
2001	5	3	0.6667	0.3333	0	0	0
2000	5	4	0.5	0.5	0	0	0
1999	5	5	0	1	0	0	0
Total			1.6667	2.2333	0	0.3667	0.7333

$$\frac{W(22)}{100} \times \hat{x}^{(0)} = 94.15/100 \times 0.2032 = 0.1913$$

Consequently, the result we get by using the forecasting grey-markov model to predict the current annual increment in *DBH* of "S" Masson pine in 2004 is 0.1913cm.

2.6 Forecasting effect checking of model combination of grey-markov

The forecasting current annual increment in *DBH* of "S" Masson pine in 2004 is 0.1913cm, contrasting with the actual growth value of "S" in 2004 (0.2cm). However, the fitting precision of established grey-Markov combination model is rather high (95.66%).

2.7 Forecasting effect checking of two models

The formula 15 was used to check the forecasting results of GM (1,1) and model combination of grey-markov. The history matching average relative error of the forecasting model combination of grey-Markov is 4.90%, while the grey model is 13.36%. Therefore, the fitting precision of the forecasting model combination of grey-Markov is obviously higher than that of the pure grey model.

Therefore, we can use the grey-markov combination model to predict the current annual increment in *DBH* of "S" Masson pine in 2005. If we use the model for long-term prediction, we can write the forecasting state and values in the coming years down in the data sequence and rebuild the Markov chain forecasting matrix table (Table 3) to make prediction for each year. The modeling course is as above. The forecasting result shows that the most current annual increment in *DBH* of "S" Masson pine in 2005 is 0.1415cm.

On the same principle, we can also build the forecasting grey-markov model of "F" to predict the future current annual increment in *DBH*. The forecasting result shows that the current annual increment in *DBH* of "F" Masson pine in 2005 is 0.1494cm[22,49].

3 Discussion

The present results of PWN invasion in 1996 show that after the attack, no matter in which way the Masson pines fell to the ground (naturally or by cutting), the influence on the *DBH* growth of the remaining pines around is significant, while that on the height growth is not significant. The results suggest that after the invaded trees are removed or naturally fallen on the ground, the competition of the trees around will become less tight. As the trees get more space, sunshine and nutrients, the growth peak occurs. Also the total increment and mean increment of the average trees in a PWN attacked site are higher than those of the trees growing in an unattacked site. After a series of protection measurements conducted in the sample plot such as removing the invaded pines and using pesticides (Fenthion, Fenitrothion, Prothiofos etc.), the annual mean increment of remaining Masson pines generally increased[11]. David reported that the crowding of trees decreases growth and survival of the mean tree. In the process of growing trees may encroach upon the resources of adjacent trees, depleting these resources and interfering with a neighbor's access to them. When any tree falls below some minimum resource level it dies, and resources will be freed up for others[50]. Wu *et al.* also pointed out that after the invasion of PWN, the attacked pine trees dried up. Suppressed and subarbor trees nearby could gain more space, sunshine and nutriment, and the growth vigor may increase. This can lead to recovery and better functioning of the forest ecosystem in a short period[51].

On the basis of the present results we could conclude that after PWN invasion the pine forest resource was seriously damaged. Loss of large number of pine trees can change the structure and function of the previous pine forest ecosystem[52]. Removal of infected trees as one of management measures can also influence the structural changes of forest vegetation. However, from the view point of system evolution, PWN as an exotic selection factor urged the whole ecosystem exposed to the more stable direction. It changed the unreasonable pattern of continuity distribution in the former pure pine forest, and affected the community structure in the succession direction of the climax stage. In Zhejiang province, the climax stage is broad-leaved forest or mixture of pine and broad-leaved tree species.

Accordingly, as for the ecosystem restoration of the degraded Masson pine forest caused by PWN, the following suggestions were put forward: When the undamaged but overly dense or new damaged pine forest are concerned, moderated thinning should be carried on, thus increasing the growth vigor of remaining Masson pines. After that, the formed forest type can maintain rather high species diversity, and then enhancing the resistance ability of pine forest to PWN. But as for the seriously damaged pine forest, such measures as removing the attacked trees and supplementing a certain number of broadleaf trees could also be taken, thus updating the forest into a mixed one, which not only maintain the stability of community structure and function, but also increase the resistance ability of pine forest.

While competition for resources is simple to describe, it is challenging to represent this explicitly in a workable mathematical form. Thompson re-calibrated the mixedwood growth model to forecast the Lodgepole pine (*Pinus contorta*) growth and yield in mixture so as to improve both the short- and long-term projection accuracy of the model for boreal mixedwood stands in Alberta, Canada[53]. The simulation accuracy of Masson pine growth is good for the average trees in both PNW attacked and unattacked sites, without the need to be rectified. However, as for the healthy trees around the stump and fallen dead trees, the simulation accuracy for height growth is good, but the accuracy for *DBH* growth should be fitted by using grey-markov combination model to get a better result. A series of GM(1,1) models and grey-markov models can be used in growth prediction of both infected and normal Masson pine forest factors.

Grey forecasting model was firstly established by a Chinese expert, which was thus probably not so world famous. However markov model has been applied extensively in both the domestic and international research fields. Our study combined the Chinese Grey forecasting model with the markov model inventively, with a good predictive outcome, which will not only advance more and more acknowledgement of the grey model buy also increase the accuracy and application of Markov model.

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