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Traits of Masson Pine Affecting Attack of Pine Wood Nematode

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Abstract

Masson pine characteristics were analyzed in five sample plots in Zhejiang Province, China. *Bursaphelenchus xylophilus* (Steiner et Buhrer) Nickle (pine wood nematode, PWN) carried by *Monochamus alternatus* predominately attacked Masson pines in the lower diameter classes. Among the 10 tree characteristics examined, mean crown width, percentage of bole with crown, 5-year cumulative diameter growth, and resin amount showed significant variation between successfully attacked and unattacked trees. The attacked trees had a lower percentage of the bole covered with tree crown, lower crown width, lower radial growth in the last 5 years, and produced less induced resinosis than unattacked trees. Results allowed for effective ranking of the pine forest based on individual tree resistance to PWN. This index of resistance should be considered throughout the development of an "Evaluation Criterion and Indicator System". The preceding ranking can be used to evaluate the resistance and resiliency of the pine forest ecosystem to PWN's invasion, which is similar to Pest Risk Analysis (PRA).

Key words: *Bursaphelenchus xylophilus*; invasion; *Pinus massoniana*; resistance; susceptibility; tree characteristics.

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The pine wood nematode (PWN), *Bursaphelenchus xylophilus* (Steiner et Buhrer) Nickle (Nematoda: Aphelenchoididae), originating from North America, causes the destructive pine wilt disease (Dropkin et al. 1981; Bergdahl 1988). Although indigenous in North America, the PWN has been reported from Japan (Mamiya 1988; Oku 1995), Korea and China (Sun 1982; Cheng 1983) in Asia, and Portugal in Europe (Enda 1997; Mota et al. 1999). *B. xylophilus* causing pine wilt disease has thus become a worldwide quarantine pest.

In China, the direct economic loss caused by the pine wood nematode is estimated to be approximately RMB 2.5 billion with indirect economic loss exceeding RMB 25 billion (Yang 1995; Zhang and Luo 2003; Wu 2004). The most important vector for the transmission of the pine wood nematode in Japan and China is the Japanese pine sawyer beetle (PSB), *Monochamus alternatus* Hope (Coleoptera: Cerambycidae). It has been recorded on more than 15 species of *Pinus*, plus several species of *Abies, Cedrus, Picea,* and *Larix* (Yang 2003). Loss from Masson pine, *Pinus massoniana* Lamb, an indigenous species found in 19 southern provinces of China, has counted for 40–50% of tree mortality in southern China (Wang et al. 1993; Shen and Lan1995; Zhao and Xu 1998).

Previous studies have shown that the spatial distribution of pine trees attacked by PWN is random within a forest (Chai and Jiang 2003). The selective and patchy distribution of mortality suggests that *M. alternatus* may be limited by the abundance and distribution of susceptible host trees. Identifying the characteristics of susceptible hosts may contribute to a broader understanding of both the biology of the beetle and the resistance mechanisms of pine forest ecosystems to PWN.

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Table 1. The diameter-at-foot and diameter-at-breast-height (DBH) of Masson pines

Sample plot	Tree number	DBH (cm)	Basal diameter (cm)	Sample plot	Tree number	DBH (cm)	Basal diameter (cm)
1	38	9.5	12.9	5	45	4.3	8.2
1	39	14.0	17.8	5	47	5.1	8.0
1	41	12.6	16.9	5	48	5.5	10.0
1	42	20.6	25.5	5	100	2.4	4.0
1	119	23.5	29.1	5	101	4.5	7.7
1	123	11.7	14.2	5	102	2.4	4.7
1	124	11.8	15.0	5	107	3.8	6.5
1	127	17.6	21.1	5	138	2.3	5.7
1	143	14.5	16.2	5	139	1.8	3.8
1	144	18.3	21.9	5	140	2.0	5.5
1	187	9.6	12.2	5	141	2.2	4.1
1	195	10.5	13.9	5	152	1.2	1.7
1	199	10.1	13.1	5	154	3.2	7.6
1	202	15.5	20.5	5	156	1.1	1.8
1	205	10.9	14.15	5	216	11.0	14.0

Pinus trees rely on resinosis as their defense against attack by burrowing insects and fungi. The vigor of host trees has been identified as the main factor affecting the ability of a tree to defend itself (Berryman 1982). Tree vigor, usually indicated by measures of radial growth, may be influenced by senescence, defoliation, pathogens, and other stress factors (Coulson 1979; Kaufman and Ryan 1986; Yoder et al. 1994; Nebeker et al. 1995; Muhammad et al. 2005).

The Masson pine is susceptible to attack by PWN. The objectives of this study were to identify some characteristics of pine forest related to the susceptibility (or resistance) to PWN. The final aim is to construct an "Evaluation Criterion and Indicator System" on resistance and resilience ability of a pine forest ecosystem to PWN's invasion, closely related to Pest Risk Analysis (PRA).

Results

Relationship between basal diameter and DBH of Masson pine

The measured basal diameter and diameter-at-breast-height (DBH) value of 30 Masson pines are listed in Table 1. Through linear regression analysis, the relationship equation of basal diameter and DBH of Masson pine was established:

$$Y = 1.110x + 2.178 \quad R = 0.991^{**} \tag{1}$$

The result showed that this equation was reasonable enough to use the basal diameter value of stumps of fallen trees to calculate the DBH value before they were removed.

Diameter class distribution rule of attacked Masson pines

From equation (1), we calculated the basal diameter value of stumps in plots 1–4, respectively. Based on census data of every individual in 2003 and 2004, it was concluded that the distribution rule of the diameter class of Masson pines were grouped by inland (Fuyang city) and island (Zhoushan city), respectively. When dividing the diameter class, we found that the mean DBH of inland Masson pines was 12.4 cm. Consequently, 4 cm was regarded as a unit, while the mean DBH of island Masson pines was 7.0 cm. Therefore 2 cm was treated as a unit. Finally, we determined the pine number of different attack classes according to the diameter class. Also the percentage of every attack class in each diameter class was analyzed.

Plots 1 and 2 represent a pure Masson pine stand, and a mixture stand of inland Masson pine and broadleaves, respectively. The analytical results of the diameter survey are shown in Figures 1 and 2. In the inland areas, both in pure forest and in forests of misture Masson pine, the most attacked pines were in the lowest two diameter classes (2–10 cm DBH). *M. alternatus* contributed to the mortality of 70% of the Masson pine in the lowest two diameter classes in pure Masson pine forest, and to 50% in the forest of mixture Masson pine.

Plots 3 and 4 represent a pure Masson pine stand, and a mixture stand of island Masson pine and *P. thunbergii,* respectively. The diameter survey of Plots 3 and 4 is shown in Figures 3 and 4. In the island setting, both in pure forest and in the mixture forest of Masson pine, although every diameter class is susceptible for attack, the most attacked pines were in the lowest two diameter classes (2–6 cm DBH). *M. alternatus* contributed to the mortality of 54% of the pines in the lowest two diameter classes in pure forest and to 46% in mixture forest.

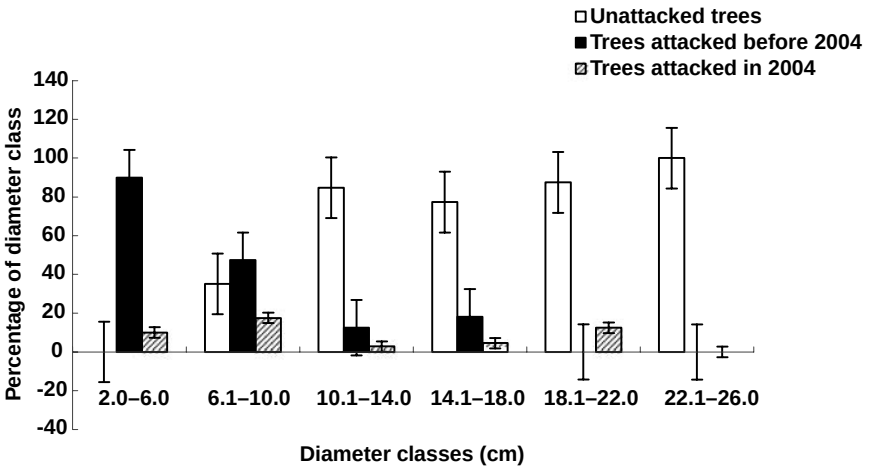

Figure 1. Percentage of infected and healthy Masson pines in different diameter-at-breast-height (DBH) classes (sample plot 1).

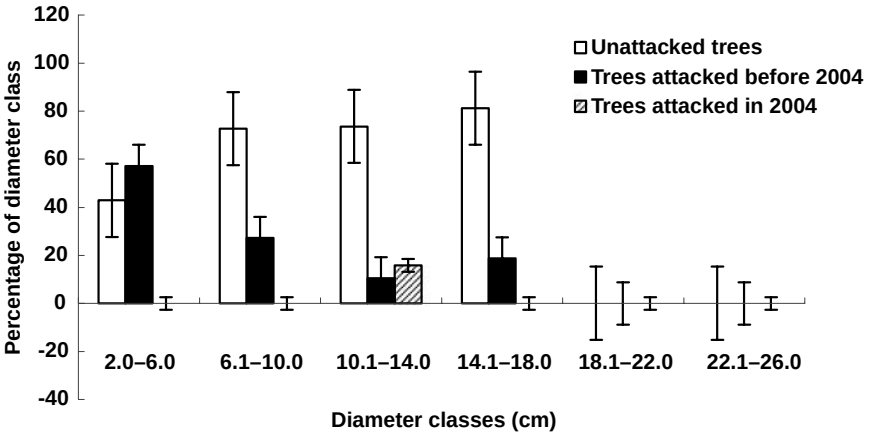

Figure 2. Percentage of infected and healthy Masson pines in different diameter-at-breast-height (DBH) classes (sample plot 2).

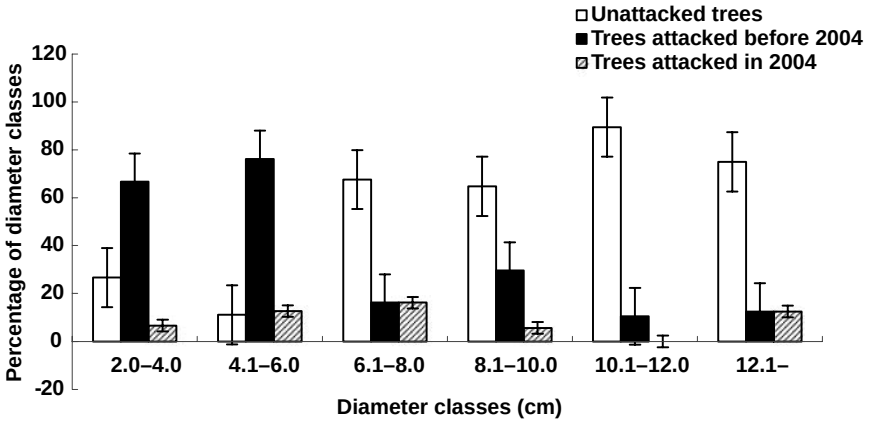

Figure 3. Percentage of infected and healthy Masson pines in different diameter-at-breast-height (DBH) classes (sample plot 3).

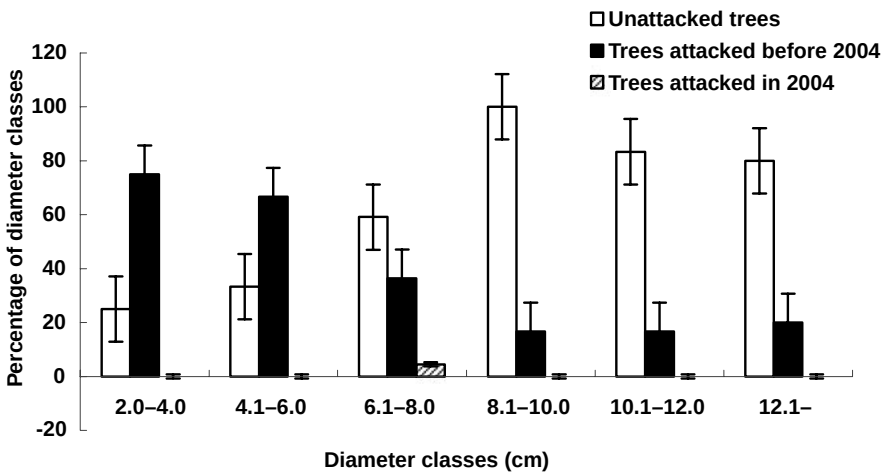

Figure 4. Percentage of infected and healthy Masson pines in different diameter-at-breast-height (DBH) classes (sample plot 4).

Table 2. Mean comparison of tree characteristics between unattacked and attacked Masson pines

Tree characteristics	Unattacked trees	Pre-2004 successfully attacked trees	2004 successfully attacked trees
DBH (cm)	14.362a	10.625a	10.500a
Height (m)	10.742a	9.05ab	6.75b
Bole length (m)	10.14a	8.48a	4.75b
Mean crown width (m)	2.46a	1.25b	1.13b
Crown volume (m^3)	7.058a	1.925b	3.063ab
Percentage of bole with crown (%)	57.8a	28.8b	22.1b
5-year cumulative diameter growth (mm)	16.988a	8.875b	8.250b
Mean phloem thickness (mm)	5.679a	5.425a	2.750a
Canopy age (years)	19.15a	18.00a	16.75a
Resin category	2a	4b	4b

A logarithmic transformation was applied to crown volume and an anti-sine transformation was applied to percentage of bole with crown prior to analysis of ANOVA. Means within rows followed by the same letter are not different significantly ($P > 0.05$). DBH, diameter-at-breast-height.

Tree characteristics

Of the tree characteristics analyzed, mean crown width, percentage of bole with crown, 5-year cumulative diameter growth, and resin amount showed significant differences among unattacked Masson pines and successfully attacked pines (Table 2). Successfully attacked trees had significantly lower growth rates during the last 5 years; they also had a lower percentage of bole with crown, and smaller crown volume. The resin amounts in successfully attacked trees were significantly greater than in unattacked ones, which meant that unattacked pines were more resinosis than attacked ones. Or, this shows that unattacked trees suffer from lower resin pressure than attacked trees.

Discussion

Susceptibility (resistance) of Masson pine to the attack of pine wood nematode was associated with tree diameter, mean crown width, percentage of bole with crown, 5-year cumulative diameter growth, and induced resin amount. The result of diameter surveys showed that the most heavily attacked pines were in the lower diameter classes. The results were similar in both inland and island settings, as well as in pure and mixed forests. Small diameter has been a common characteristic of host trees susceptible to attack by tree-killing *M. alternatus* (Chen 2001; Chai and Jiang 2003). Smaller diameter trees might provide a more suitable habitat or food source for attacking adults and developing offspring because of the decreased host vigor and growth potential (Zai et al. 1992).

In contrast with inland, every diameter class of Masson pine can be attacked (including pure and mixture forest) in the island setting. The reason might be that the growth potential of pines is worse than those in the same inland conditions because of the harsh climate conditions found on islands. Consequently, the island Masson pines appeared thinner and had deficient growth potential. Thus, after the invasion of pine wood nematode, the pines of every diameter classes in island showed the

susceptibility to the attack. However, the most attacked pines remained in the lowest two diameter classes. This observation is consistent with the inland pines.

Our results showed that the most attacked pines were in the lower diameter classes. Chai et al. (1997) reported that when the female *M. alternatus* layed eggs, most of the oviposition and incision was in the area where bark thickness was 0.2–0.4 cm. Only a little incision appeared when the bark thickness was less than 0.1 cm. This is a result of the fact that the egg is a long ellipse object with a length of about 0.4 cm and a breadth of about 0.1 cm. There must be a minimum threshold (about 0.1 cm) for bark thickness of attacked Masson pines. With the decline of diameter class the bark thickness decreased, leading to increased harm rate. If the bark thickness reduced to less than 0.1 cm, the harm rate would decrease instead because *M. alternatus* could hardly lay eggs on bark that is too thin. However, attacking beetles did not choose their host trees on the basis of phloem thickness in our study.

The greater mean crown width and the percentage of bole with crown of tree, the greater was the resistance ability of pine. In contrasting, the more susceptible the pine was, which might be due to the greater mean crown width and the percentage of bole with crown covering, the smaller the proportion of the bole. This provided similar evidence to previous studies, in which the probability of being attacked by boring insects declined with decreasing bole size.

Defoliation and pruning could possibly increase susceptibility to boring insects or associated species (Wright et al. 1979; Miller and Berryman 1986; Christiansen and Fjone 1993). The tendency of successfully attacked trees to have a smaller crown suggested that crown size may be related to resistance. Increased susceptibility of trees with a lower proportion of the bole with crown covering could be due to the higher rates of successful landings for boring insects on such trees. Branches may inhibit incoming beetles from locating and landing on the bole. Although beetles might land and move around at the lower part of the bole before attacking, *M. alternatus* has been observed to usually prefer to land on the upper bole, and oviposit at the middle or the upper middle part of the bole (Stock 1991; Chen et al. 2001).

The resinosis study showed that trees with higher resinosis were less susceptible to the attack by *M. alternatus* than trees with lower resinosis. The induced resinosis could be responsible for repelling attacks by the beetles, inhibiting the establishment of blue-stain fungi associated with boring insects, deterring oviposition and increasing brood mortality (Reid et al. 1967; Berryman 1969; Berryman and Ashraf 1970; Christiansen 1985).

The decline in host vigor, as indicated by declining recent radial growth from unattacked to successfully attacked trees, suggested that *M. alternatus* might not be able to overcome the defense of more vigorous hosts. Other studies have also shown that the susceptibility to boring insect attacks is associated with reduced growth and vigor (Ferrel et al. 1973a, 1973b; Ferrell and Hall 1975; Larsson et al. 1983; Hard 1985; Waring and Pitman 1985; Lessard and Schmid 1990; Shore et al. 1999). Beetles might be able to recognize low-vigor hosts and preferably select them for attack. On the other hand, faster-growing trees were less susceptible to attack by *M. alternatus* than slower-growing trees, which might be a result of the higher quantities of induced resinosis observed on fast-growing trees. Host vigor may also affect qualitative aspects of the induced response, for example, relative amounts of toxic compounds or viscosity (Bordasch and Berryman 1977; Wong and Berryman 1977; Raffa et al. 1985; Lewinsohn et al. 1993; Rohde and Lunderstadt 1996; Nagy et al. 2000). Other related studies showed that reduced photosynthetic ability might affect the induced response, which depended on the efficient translocation of current photosynthate to the invasion site (Christiansen and Ericsson 1986; Miller and Berryman 1986). Finally, the preference of *M. alternatus* for low-vigor hosts was shared by most other species of boring insects (Rudinsky 1962). Stressed and downed trees might emit volatiles that enable insects to locate weakened hosts. Furthermore, weakened hosts possess potentially mitigated defense systems, which would increase the likelihood of successful brood production (White 1969).

The results of this study found five indices (tree diameter, mean crown width, percentage of bole with crown, 5-year cumulative diameter growth, and resin category) of pine forest related to the resistance by PWN. This observation should be considered in the development of an "Evaluation Criterion and Indicator System (ECIS)" of resistance and resilience ability of pine forest ecosystem to PWN's invasion. The Evaluation Criterion and Indicator System are closely related to Pest Risk Analysis.

Materials and Methods

Site description

The research area was located at Fuyang and Zhoushan city of Zhejiang Province in Southeast China. The Fuyang city is situated at the northwest part of Zhejiang Province. It comprises part of 17 towns and eight counties, with an area of 1 830 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 1 000 mm and annual temperature 16 °C. The Zhoushan city is located in the shore islands of Zhejiang Province. It comprises part of 98 islands, with an area of 22 200 km^2 (29°32′–31°04′ N, 121°30′–123°25′ E). The area has a northern subtropical monsoon ocean climate with high air temperatures and relative humidity. The mean annual precipitation is about 1 500 mm and annual temperature 17 °C (Regionalization Office of Forestry Department in Zhejiang Province 1991).

The five uniform (30 m × 30 m) Masson pine experimental plots were selected in Fuyang (inland) and Zhoushan (island) counties in Zhejiang Province. Plot 1 is located on the fourth compartment in Dongshan village of Fuyang county (30°04′51.4″ N, 119°57′5.1″ E) at an altitude of 98 m above sea level. In 2004 (the year of the present investigation), the trees were 25 years old, and the stand density was 2 533 trees per hectare. The dominant tree species in the arbor layer was *Pinus massoniana*.

Plot 2 is located on fourth compartment in Dongshan village of Fuyang county (30°04′57.3″ N, 119°56′58.6″ E) at an altitude of 117 m above sea level. In 2004, the trees were about 25 years old, and the stand density was 1 467 trees per hectare. The dominant species in the arbor layer include *P. massoniana* and *Schima superba* Gardn. et Champ.

Plot 3 is located on the 31st compartment in Zhu Jiajian village of Zhoushan county (29°55′54.3″ N, 122°24′0″ E) at an altitude of 36 m above sea level. The stand density was 1989 trees per hectare. The dominant species in the arbor layer was *P. massoniana*.

Plot 4 is located on the 13th compartment in Zhu Jiajian village of Zhoushan county (29°55′50.6″ N, 122°20′43.6″ E) at an altitude of 24 m above sea level. The stand density was 1 500 trees per hectare. The dominant species in the arbor layer include *P. massoniana* and *P. thunbergii* Parl.

Plot 5 is located on the third compartment in Dongshan village of Fuyang county (30°04′42.8″ N, 119°57′05.1″ E) at an altitude of 86 m above sea level. The stand density was 1 156 trees per hectare. The dominant species in the arbor layer was young *P. massoniana*.

In 1996 the pine wilt disease attacked the pines of all experimental plots excluding Plot 5. The Forest Pest Control & Quarantine Station of Zhejiang Province attempted to control the crisis by cutting down the invaded trees and using chemical control against the nematode (Jiang 2001). Consequently, stumps of fallen trees were left in the stand.

In order to obtain data from the attacked trees, we use the technique of inspecting each individual tree in the five plots. The diameter at breast height (including basal diameter of stump), height and crown width of the trees were measured, and each tree was individually labeled in 2004 (Meng 1995).

Separating pine wood nematode

Sixty weakened Masson pine trees were selected from Plots 1–4 (15 for each plot). Wood blocks were chopped into spills, wrapped with gauze, and finally placed into the filler for soaking. The use of the "Baermann funnel method" is an effective and sustainable technique to evaluate the pervasiveness of pine wood nematode penetration within the dead pine trees found in our study area. The results of this experiment reveal that pine wood nematodes were found in three areas: the lateral root of the Masson pine, the chamber, and the feeding wound of PSB.

Establishment of a relationship between basal diameter and DBH of Masson pine

According to the diameter class value, 15 middle-aged and young Masson pines were selected in plots 1 and 5. The basal diameter and DBH were then measured in order to establish the regression equation. In addition, we used the basal diameter value of stumps of fallen trees to calculate the DBH value before they were removed.

Diameter class survey of Masson pines

In Plot 1 (Pure Masson pine stand inland), Plot 2 (mixture stand of Masson pine and broadleaves inland), Plot 3 (Pure Masson pine stand on the island), Plot 4 (mixture stand of Masson pine and *P. thunbergii* on the island), basal diameter of pine stump, species and DBH of every tree greater than 1.3 m in height were recorded. The extent of diameter class of Masson pines were defined according to the following rules: when mean diameter was above 12 cm, consider every 4 cm as one diameter class; and when the mean diameter was 6–12 cm, consider every 2 cm as one diameter class (Academy of Forest Inventory and Planning of Forestry Ministry 1984). The pines were also classified according to one of the following conditions: 1, healthy; 2, trees with successful attack in 2004 (fading or red color indicating PWN attack); and 3, trees with successful attack before 2004 (stumps and fading red or grey color indicating PWN attack).

Tree characteristics

In September 2004, 30 healthy trees, trees with successful attack in 2004, and trees with successful attack before 2004 were respectively selected in Plots 1–4. To ensure that the sampled trees were independent and not a result of a spillover attack from adjacent sampled trees, all attacked trees had at least two mature unattacked Masson pine trees between them. The unattacked trees were selected as controls.

The following variables were measured for each tree: DBH (cm), height (m), mean crown width (m) (from two measurements taken at 90° angles to each other), mean phloem thickness (mm) (derived from measurement taken on the east and west aspect at 1.3 m), crown length, bole length, 5-year cumulative diameter growth (measured with increment borer), canopy age (judged by complete and continuous whorls of branches) and resin amount.

Resin rating (Figure 5) was configured according to the following method: after boring a round hole of 2 cm diameter into the bole phloem, the resinosis situation was observed 12 h

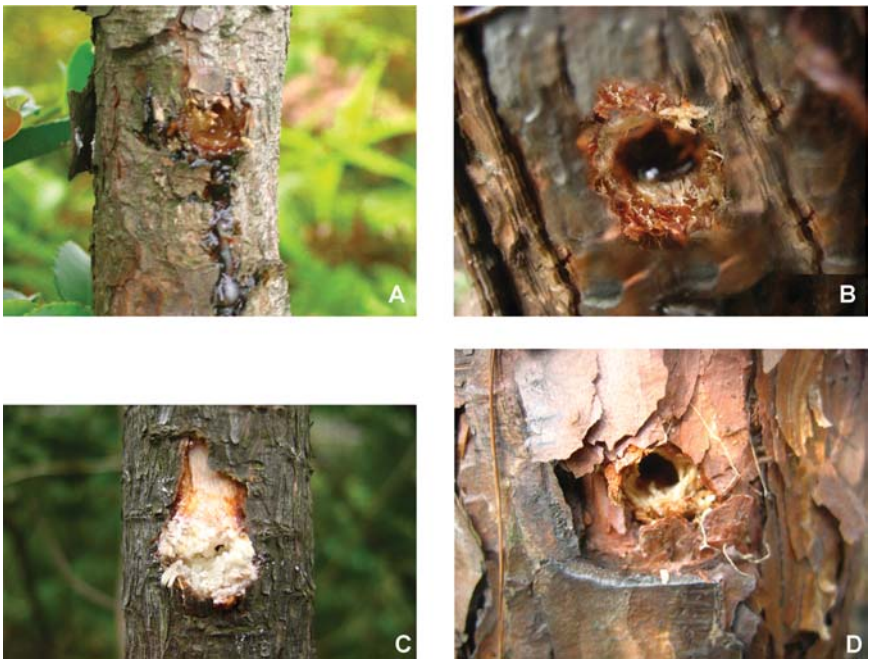

Figure 5. Measuring resin pressure.

(**A**) Level 1, resin could fluently stream out of the round hole.
(**B**) Level 2, resin stream is pronounced but covered only the bole phloem.
(**C**) Level 3, only grained turpentine appeared in the round hole.
(**D**) Level 4, no resinosis but a slight resin odor was noticeable.

later. Divided by different situations of resinosis, a resin rating was given as follows: 1. resin could fluently stream out of the round hole; 2. the resin stream is pronounced but covered only the bole phloem; 3. only grained turpentine appeared in the round hole; and 4. no resinosis but a slight resin odor was noticeable (Chai and Jiang 2003).

At the same time, the following two variables were calculated for each tree: crown volume (m^3) was estimated using mean crown width and the crown length to calculate the volume of cone. Percentage of bole with crown was estimated using the crown and the bole length.

Data analysis

Linear regression analysis was carried out using basal diameter as the independent variable while DBH was the dependent one. Data from the diameter distribution survey were graphed to determine the diameter distribution of attacked trees in plots 1–4. Tree characteristics were analyzed for differences among attack classes (unattacked trees, trees with successful attack in 2004 and trees with successful attack before 2004) and plot using a three-factor nested ANOVA. Attack class and sample plot were entered in the model as fixed factors, and individual trees were nested under the preceding factors and entered as a random factor. A logarithmic transformation was applied to crown volume; an anti-sine transformation was applied to percentage of bole with crown prior to analysis to correct for non-normality. Significant ANOVAS ($P < 0.05$) were followed by LSD multiple comparisons test. The data were analyzed using SPSS.

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