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RESEARCH ARTICLE

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Schima superba as a fuelbreak: Litter combustibility of three tree species with five water content levels using a cone calorimeter

Abstract To determine the suitability of *Schima superba* Gardn. et Champ as a fuelbreak, we compared and analyzed the flammability characteristics of tree litter from three trees commonly grown in south China, i.e., *Pinus massoniana* Lamb., *Cunninghamia lanceolata* (Lamb.) Hook., and *S. superba*, using a cone calorimeter at five different water content levels. Water content levels of 10%, 15%, 20%, 25% and 30% for the litter were manually produced with a new technique of adding water to dry litter. The cone calorimeter utilized a radiant heat intensity for leaf litter of 20 kW/m^2 (510°C) and for twig litter of 30 kW/m^2 (608°C). Results show that fixing the water content level by adding water with a pipette was an acceptable technique. For *S. superba*, compared to *P. massoniana* and *C. lanceolata*, 1) the heat release rate (HRR) was slower and lower; 2) the total heat released (THR) from the material was lower and started later in the burning process; and 3) except for the 10% water content, pkHRR/TTI was less. These results show that overall, *S. superba* was the best of the three species to be used as a fuelbreak in south China.

Keywords fuelbreak, litter, water content, cone calorimeter, combustibility, *Schima superba*, *Pinus massoniana*, *Cunninghamia lanceolata*

1 Introduction

Pinus massoniana Lamb. and *Cunninghamia lanceolata* (Lamb.) Hook. (Chinese fir) forests thrive in mountainous areas of southern China, particularly in the Zhejiang Province. These two forest types comprise 67.5% of the total forested area and 75.3% of the total tree volume in the Zhejiang Province (Forestry Department of Zhejiang Province, 2005). However, *P. massoniana* and *C. lanceolata* forests could become fire disaster areas as the forest litter increases. According to the statistical reports of forest fire disaster in the Zhejiang Province, 87.6% of forest fires between 1988 and 2002 occurred in either 1) *P. massoniana* or 2) mixed conifer and broadleaf forest stands, accounting for 90.9% of the total burned area (Mao et al., 2004). In these forests of southern China, fire resistance belts are composed primarily of *Schima superba* Gardn. et Champ. These trees, to a certain extent, can slower advance of surface fires and forest crown fires (Weng, 1998; Tian et al., 2003). Nevertheless, the different burning conditions and litter characteristics of *S. superba*, *P. massoniana*,and *C. lanceolata* are not well defined.

To conduct fire protection research, a cone calorimeter developed by the National Institute of Standards and Technology (NIST), USA, in the 1980s, is often used to determine burning parameters of forest litter. The cone calorimeter is a small-scale, new generation apparatus used to measure the burning capability of polymers. Based on oxygen consumption, it can detect differences in the burning characteristics of wood materials under the same conditions as an outdoor heat source. Several burning parameters can be quantified, including time to ignition (TTI), heat release rate (HRR), total heat release (THR), effective heat of combustion (EHC), total smoke release (TSR) and other quality change parameters. Compared with traditional methods such as the oxygen index method, the vertical burning method and the horizontal burning method, the cone calorimeter has the advantage of determining more parameters with the experimental results

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being closer to the actual conditions on the ground (Gilman et al., 1997; Hshieh and Beeson, 1997; Li and Wang, 1998; Tian et al., 2001; Wang and Chen, 2006). To determine the feasibility of *S. superba* as a fuelbreak, we compared and analyzed the flammability characteristics of tree litter from three trees commonly grown in southern China, i.e., *P. massoniana*, *C. lanceolata*, and *S. superba*, using a cone calorimeter at five different water content levels.

2 Materials and methods

2.1 Site description, research plots, and sampling

Litter for the three forest types was obtained from the Tianmu Mountain in Zhejiang Province (29°29′N, 119°12′E) which is a national nature reserve. This area has a typical subtropical monsoon climate characterized by an average annual temperature of 8.8–14.8°C and rainfall of 1390–1870 mm. The annual dry and rainy seasons are clearly distinct, with the rainy season beginning in May and lasts until September. Physical features include high and steep rock faces with various complex surface landforms. Soils are often found as patches of fields on hills, in valleys or as pockets in mountain areas. The typical soil types in order of abundance include what is locally known as red earth, yellow earth and yellow brown soil.

Plant species are plentiful with abundant high forests of broadleaf evergreen trees and conifers of *P. massoniana* or *C. lanceolata*. The low forest or bush types include: *Indocalamus latifolius* (Keng) Mcclure, *Loropetalum chinense* (R. Br.) Oliver, *Lindera glauca* (Sieb. et Zucc.) Bl., *Quercus fabric* Hance, *Wisteria sinensis* Sweet, *Rubus chingii* Hu and *Camellia oleifera* Abel. Grass types are also found in the Tianmu Mountain, such as *Dicranopteris dichotoma* Bernh., *Smilax china* Linn., *Diplopterygium laevissimum* (Christ) Nakai, *Liriopis platyphyllae* Wang et Tang, *Trachelospermum jasminoide* and *Rubus corchorifolius* Linn.

Litter collection was made during the season of fire susceptibility after three continuously sunny days. In this area, the fire season was from early February to late April and from early November to late December, with litter collected in December, 2006. A total of 19 research plots, 10 m × 10 m, were established in 25–30-year-old *P. massoniana* (five plots), 10–25-year-old *C. lanceolata* (five plots), and 11-year-old *S. superba* (nine plots). Within these plots, eight 1 m × 1 m subplots were designated. For each subplot, 100 g of leaf litter and 100 g of twig litter were collected and taken to the laboratory for analysis.

2.2 Experimental procedures

Firstly, each leaf and twig litter subplot sample was divided into two 50-g subsamples. For one 50-g subsample, the water contents of both leaf and twig litter were determined to find the range of water content levels from the unaltered field samples so that appropriate water content levels for the experiment could be selected. Then, the other 50-g subsample was dried at 80°C to constant weight. The dried samples were adulterated in terms of tree species and mixed thoroughly to obtain a sample of leaf litter and a sample of twig litter for each species.

Next, the mixed samples were separated to five samples of 20 g for leaf litter and 50 g for twig litter for each tree species, and each of these samples were placed in a two-layer hermetic bag. To get better comparability, all the twigs chosen were 8 cm long and 0.7 cm in diameter. Then, water was added to each set of bags using a pipette (with an accuracy of 0.01 mL) until the water content reached 10%, 15%, 20%, 25% and 30%, and the volume of water was recorded (Table 1). To test if the water content changed when thoroughly mixed, the bags were placed on a shaking table for 10 d until the water was thoroughly mixed with the leaves or twigs. Then, the water content level of each leaf litter and twig litter bag was measured again and compared to pre-shaken levels.

Table 1 Dry weights of leaf and twig litter and their water mixtures to test the five water content levels after thoroughly mixed

water content /%	dry leaf weight/g	leaf-water mixture/mL	dry twig weight/g	twig-water mixture/mL
10	20.00	2.22	50.00	5.55
15	20.00	3.53	50.00	8.82
20	20.00	5.00	50.00	12.50
25	20.00	6.67	50.00	16.67
30	20.00	8.57	50.00	21.43

Afterwards, for each tree species, litter samples from the adulterated subplot samples were used to make samples with dry weights equal to 5.00 g (leaf litter) and 15.00 g (twig litter) with wet weights determined for each of the five water content levels (Table 2). A total of 45 subsamples of both leaf and twig litter (5 water content levels × 3 tree species × 3 samples) were placed in a cone calorimeter (ASTME-1354-93, ISO-5660, produced by the Flammability Test Technology Company of Britain (FTT)) to determine flammability characteristics. According to the ISO-5660 operation protocols, test samples less than 50 mm thick were put on a 100 mm × 100 mm square metal tray with sides and bottom of the sample encased using aluminum foil and covered with wire netting to prevent leaf or twig litter from falling out during the burning process. Samples were heated to a radiant heat intensity of 20 kW/m^2 (equivalent to 510°C) for leaf litter and 30 kW/m^2 (equivalent to 608°C) for twig litter. Computed litter flammability results were obtained from the cone calorimeter.

Finally, to determine if there were any cone calorimeter measurement differences between samples with manually

Table 2 Dry and wet weights of leaf and twig litter for five water content levels to test flammability characteristics in a cone calorimeter

water content /%	leaf dry weight/g	leaf wet weight/g	twig dry weight/g	twig wet weight/g
10	5.00	5.56	15.00	16.67
15	5.00	5.88	15.00	17.65
20	5.00	6.25	15.00	18.75
25	5.00	6.67	15.00	20.00
30	5.00	7.14	15.00	21.43

derived water content (the five selected water content levels) and actual field water content, one sample of leaf and twig litter for each water content level of 15%, 20%, 25% or 30% of each of the three tree species for both manually produced and actual field samples were selected (10% was not available under field conditions). These samples were prepared for the cone calorimeter, as above with identical weights. The derived and actual samples were burned in the cone calorimeter and parameters of time to ignition (TTI) and peak heat release rate (pkHRR) were compared.

3 Results

3.1 Experimental pretests and verification

The range of water content in the collected field samples was mostly between 22% and 27%, accounting for about 81.7% of the samples with a minimum of 17.4% and a maximum of 31.2%. Generally, the water content of litter in the *S. superba* plots was slightly higher than that in the *P. massoniana* and *C. lanceolata* forests. Nevertheless, water content levels for leaf and twig litter were almost the same.

When water was added to leaf and twig litter of the three species and shaken to determine the accuracy of adding water with the pipette, the water content prior to and after shaking were the same. This means that there were no differences in techniques.

Finally, to test for differences between water content of artificially made litter samples with the pipette and natural samples from the field plots, for time to ignition (TTI) and peak heat release rate (pkHRR) at water content levels of 15%, 20%, 25% and 30% for each of the three species, the cone calorimeter measurement differences were small (Table 3).

3.2 TTI, HRR, THR, and pkHRR to TTI

For the manually set water content, the average TTI of three samples for leaf (Fig. 1(a)) and twig litter (Fig. 1(b)) of *P. massoniana*, *C. lanceolata* and *S. superba* increased as water content increased. When the water content was 10% and 15%, the TTI for both leaf and twig litter of *S. superba* was shorter than that of *P. massoniana* and *C. lanceolata* (Fig. 1). However, when the water content was 20% and 25% for twig litter and 30% for both leaf and twig litter, *S. superba* TTI was longer.

For the same weight and at each water content level, the average HRR of leaf litter for the three tree species was generally in the order: *P. massoniana* > *C. lanceolata* > *S. superba*. Figure 2a presents an example of this order for HRR leaf litter at 25% water content. Meanwhile, for twig litter at 25% water content (Fig. 2(b)) the order was the same until about 178 s. From 178 to 219 s *C. lanceolata* had the highest HRR, and from 220 to 350 s *S. superba* had the highest HRR.

Table 3 Time to ignition (TTI) and peak heat release rate (pkHRR) of samples comparing four artificially versus naturally derived water content levels with leaf and twig litter of *S. superba*, *P. massoniana* and *C. lanceolata*

	artificially derived water content/%				field sample with approximate water content levels/%			
	15	20	25	30	15	20	25	30
TTI of *S. superba* leaf/s	85	108	118	159	90	109	123	146
TTI of *P. massoniana* leaf/s	103	107	113	121	97	110	114	119
TTI of *C. lanceolata* leaf/s	107	115	120	128	106	117	125	131
TTI of *S. superba* twig/s	81	121	136	151	84	120	138	146
TTI of *P. massoniana* twig/s	90	95	103	112	90	94	99	111
TTI of *C. lanceolata* twig/s	85	115	121	136	93	114	124	131
pkHRR–*S. superba* leaf/($\mathrm{kW \cdot m^{-2}}$)	89.08	82.74	72.05	57.11	89.90	83.48	76.01	51.35
pkHRR–*P. massoniana* leaf/($\mathrm{kW \cdot m^{-2}}$)	158.95	139.34	125.79	111.10	156.43	144.08	126.17	110.21
pkHRR–*C. lanceolata* leaf/($\mathrm{kW \cdot m^{-2}}$)	122.01	111.08	105.36	100.01	125.12	106.46	100.29	100.34
pkHRR–*S. superba* twig/($\mathrm{kW \cdot m^{-2}}$)	148.79	131.98	111.12	101.26	144.72	128.27	119.97	114.97
pkHRR–*P. massoniana* twig/($\mathrm{kW \cdot m^{-2}}$)	138.04	133.52	122.07	105.60	144.84	137.81	120.49	106.80
pkHRR–*C. lanceolata* twig/($\mathrm{kW \cdot m^{-2}}$)	142.86	133.97	122.59	105.03	152.65	135.12	109.84	105.03

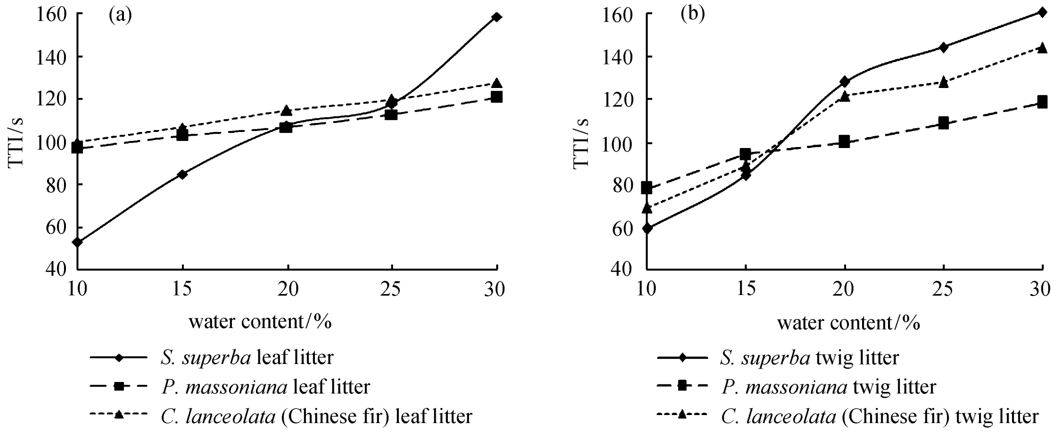

Fig. 1 Average time to ignition (TTI) for three samples of *Pinus massoniana*, *Cunninghamia lanceolata*, and *Schima superba* litter at five water content levels for (a) leaf litter at 20 kW/m^2 and (b) twig litter at 30 kW/m^2

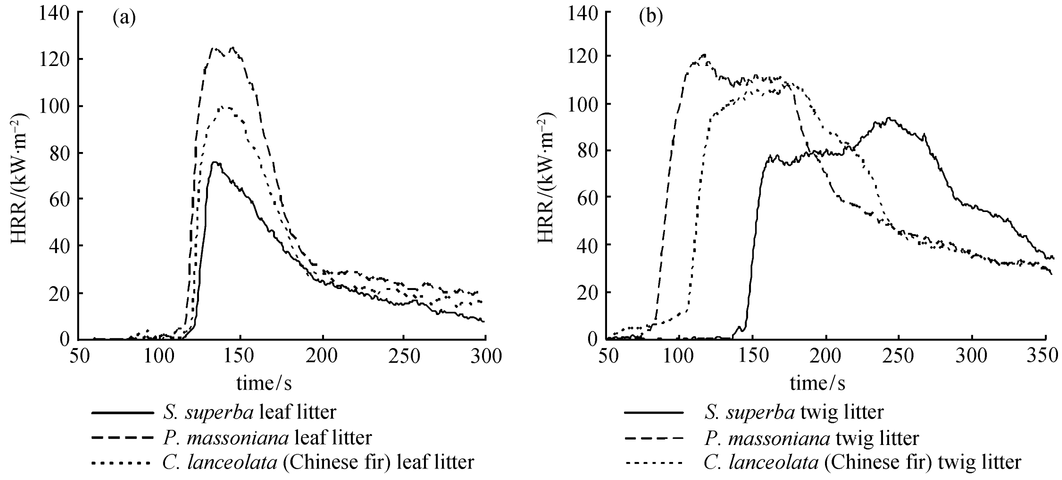

Fig. 2 Average heat release rate (HRR) for three samples of *P. massoniana*, *C. lanceolata*, and *S. superba* litter with 25% water content for (a) leaf litter at 20 kW/m^2 and (b) twig litter at 30 kW/m^2

For the same weight and at each water content level, the average THR of leaf and twig litter was also in the following order: *P. massoniana* > *C. lanceolata* > *S. superba*. With 25% water content, the average THR for leaf litter was negligible until about 120 s (Fig. 3(a)). Then, there was a sharp rise with all three species as per the above-mentioned order. For twig litter at 25% water content (Fig. 3(b)), THR increased from a negligible level at 93 s for *P. massoniana*, at 108 s for *C. lanceolata*, and at 150 s for *S. superba* maintaining the above-mentioned order to the end of the test at 350 s.

As the water content increased, the average pkHRR/TTI for leaf (Fig. 4(a)) and twig (Fig. 4(b)) litter of *P. massoniana* , *C. lanceolata* and *S. superba* decreased. For leaf litter (Fig. 4(a)), when the water content was 10%, the pkHRR/TTI of *S. superba* was the highest. However, at 15%, 20%, 25% and 30%, the pkHRR/TTI of *S. superba* was lowest. Meanwhile, for twig litter (Fig. 4(b)), the pkHRR/TTI of *S. superba* at all five water content levels was lowest.

4 Discussion

4.1 Appropriateness of the methodology

There is a strong relationship between the water content and the flammability of a material. Therefore, the water content is an important criterion in determining how easily flammable a material is. Depending on the water content, where the weight of a dry, flammable material after absorbing water could be more than twice its original weight, there could be a wide range of time to ignite. When measuring the water content levels in the laboratory, the criteria for ease of burning with a flammable material were taken from Hu (2005). Matter with water content above

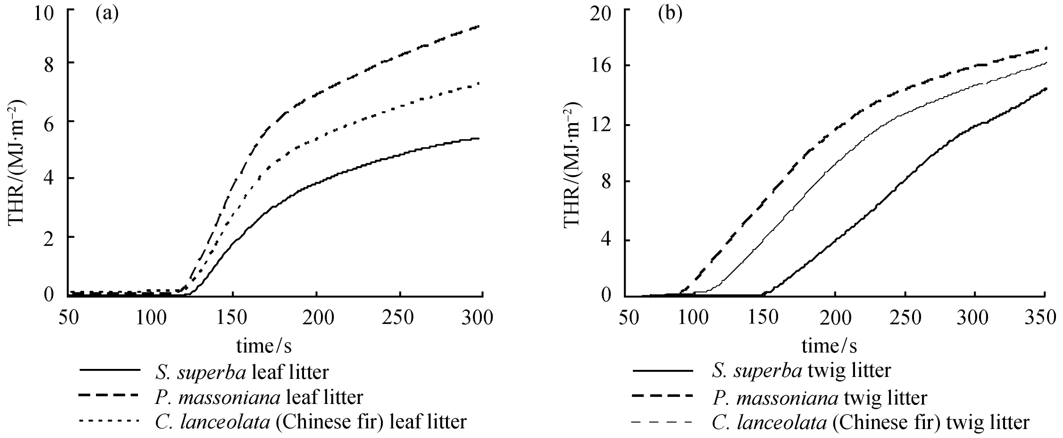

Fig. 3 Average total heat release (THR) for three samples of *P. massoniana*, *C. lanceolata*, and *S. superba* litter with 25% water content for (a) leaf litter at 20 kW/m^2 and (b) twig litter at 30 kW/m^2

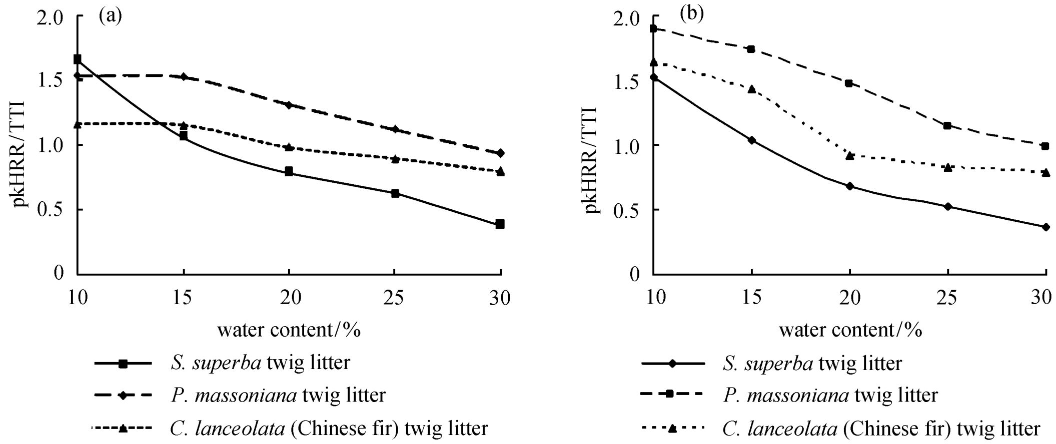

Fig. 4 Average ratio of peak heat release rate (pkHRR) to time to ignition (TTI) with three samples of *P. massoniana*, *C. lanceolata*, and *S. superba* litter at five water content levels for (a) leaf litter at 20 kW/m^2 and (b) twig litter at 30 kW/m^2

35% will not burn, from 25%–30% will burn with difficulty, from 17%–25% will burn, from 10%–16% will burn easily, and below 10% will burn very easily.

In this study, for the field samples, the minimum (17.4%) and maximum (31.2%) water contents were close to or within the selected experimental water content levels for 15%, 20%, 25% and 30%. The 10% level could be used to represent extremely dry periods that were not available this sampling year. Also, the water content levels of the three tree species were about the same as the levels between leaves and twigs. This would minimize variability among tree species.

In setting the water content level in the laboratory, a new technique was employed. First, the litter was dried and then adulterated in terms of tree species from plots into large samples standardized by size. This was to reduce the variability due to different degrees of decomposition and litter diameter. However, leaves and twigs were not broken into tiny pieces, to help maintain a constant water content level before heating. Next, water was added with a pipette. It was possible, even with thorough mixing, that the water content of the samples would change. So, the samples were measured, shaken for 10 d, and measured again. Results show no differences in water content, meaning that adding water with a pipette was an acceptable technique for fixing the water content level. This could be considered a new technique to be used for further research.

When using the cone calorimeter, it was necessary to determine the radiant heat intensity to employ for leaf litter (20 kW/m^2 or 510°C) and twig litter (30 kW/m^2 or 608°C) so that it would conform to reality. Two criteria were used. First, a burning cigarette, which is often the main cause of fire disasters, has a surface temperature between 200 and 300°C with a core temperature of 700 to 800°C. Second, these values were suitable for measuring litter TTI in a cone calorimeter. Then, it was necessary to determine if results with water content levels from field samples would be different from those set up in laboratory. For the four available water content levels (15%, 20%, 25%, and 30%) of field samples, Table 3 shows only small differences. These might result from the differences in the actual water content level. For example, the 15% water content of the laboratory sample would be compared to the 17.4% of the field sample, thus accounting for some small differences in TTI or pkHRR (Table 3). These differences were assumed to be unimportant.

Thus, pretests and verification show that the methodology used in the present study was satisfactory.

4.2 Parameters measured with the cone calorimeter

For this study, a cone calorimeter was used to measure four fire parameters: time to ignition (TTI), heat release rate (HRR), total heat release (THR) and peak heat release rate (pkHRR) to obtain the ratio of pkHRR to TTI, for comparison among three tree species. Usually, when determining flammability, a longer TTI means less chance of a fire disaster. According to Fig. 1 then, *S. superba*, with twig litter at 20%, 25% and 30% water content and leaf litter at 30%, would be less likely to burn than *P. massoniana* or *C. lanceolata*. Hu (2005) found that with typical weather conditions that produced fires, the forests in China had water content levels between 20% and 25%, meaning that *S. superba* would be a better fire-resistant tree species. However, the TTI for *S. superba* leaf and twig litter at 10% and 15% had the opposite result. Thus, in extremely dry years *S. superba* could intensify a fire.

HRR, or the rate of heat released from a material per unit of surface area, is one of most important parameters when judging the safety performance of a material with the cone calorimeter being able to reflect the dynamic change of HRR during the burning process. As Fig. 2 shows, the HRR of *S. superba* leaf litter was less than that of *P. massoniana* and *C. lanceolata*, whereas for twig litter, HRR of *S. superba* was up to about 180 s less. This meant that *S. superba* was superior as a fire resistant species in most situations.

Another variable measured with the cone calorimeter was the peak value of the heat release rate (pkHRR) or the maximum heat release rate. With a high pkHRR, the rate of material decomposition will increase, as will its volatility. Thus, a high pkHRR coupled with an increasing HRR will result in a rapid spread of the flames and a material that causes a more dangerous fire disaster (Wang et al., 2003; Lu et al., 2005). *S. superba*, with its lower pkHRR for leaf and twig litter (Fig. 2), again had shown that it was a better fire-resistant species.

Total heat release is the overall amount of heat released from material per unit area in the process of burning. However, THR depends on the quality and weight of a material. It is not related to water content. With the cone calorimeter tests, the THR of both *S. superba* leaf and twig litter was the lowest among the three species. This meant that, under similar conditions, *S. superba* was less likely to catch fire. Also, as for twig litter (Fig. 3(b)), THR remained negligibly longer than *P. massoniana* and *C. lanceolata* before increasing. This delay also meant a stronger resistance to fire.

Lastly pkHRR/TTI can be used to evaluate the potential fire disaster of a material (Li and Wang, 1998). In this regard, Petrella (1994) proposed that the combination of pkHRR/TTI and THR can evaluate the potential danger of a material in a fire disaster. Xu (2003) explained that this is because HRR and TTI are related to the quantity of heat radiated outside an object, and because THR is related to the inner energy of the material, which does not depend on environmental elements. Thus, as the pkHRR/TTI of a material increases, a fire disaster is more likely. As expected, a decrease from a higher to a lower water content level increased the pkHRR/TTI, meaning more chance of fire disaster in dry conditions. When comparing the twig and leaf litter of the three species, though, except for leaf litter at 10% water content, pkHRR/TTI of *S. superba* was always the lowest (Fig. 4). This once again meant that it was normally the most fire resistant.

4.3 *S. superba* as a fuelbreak

With its high frequency, its severe threat, and its burned areas that are difficult to recover, fire is a foremost natural disaster in forests. Therefore, fire-resistant tree species that reduce forest flammability play an important role in protecting environment. Practice has shown that *S. superba* is a fire-resistant tree. By measuring leaf and twig litter flammability of *P. massoniana*, *C. lanceolata*, and *S. superba* with different water content levels using a cone calorimeter and analyzing their differences, we have shown how and explained why *S. superba* would be a better species as a fuelbreak. Specifically, for *S. superba*, compared to *P. massoniana* and *C. lanceolata*, 1) the heat release rate (HRR) was slower and lower (Fig. 2), 2) total heat released (THR) from the material was lower and started later in the burning process (Fig. 3), and 3) except for the 10% water content, pkHRR/TTI was less. Overall, *S. superba* would be the best of the three species to be used as a fuelbreak, especially in the *P. massoniana* and *C. lanceolata* (Chinese fir) forests in southern China. Nevertheless, there are other forest tree species grown in south China. Therefore, further research could be conducted on litter of some of these other species to see how effective *S. superba* would be as a fuelbreak.

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