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Changes in the Combustion Characteristics of Living Leaves of *Pinus Densiflora* by Altitude

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Combustion tests were conducted with living leaves of *P. densiflora* to examine the combustion characteristics of this species at different altitudes. An ignition temperature tester, cone calorimeter, and smoke density chamber were used for the tests. Leaf moisture content was measured prior to combustion, yielding a range of between 148 and 177%. The temperature of non–flame ignition was 300~310 °C and did not vary with altitude. Flame ignition occurred in the samples taken at 900 m and 1300 m, but lasted for only 7 and 8 s, respectively. These two samples released similar heat, with the sample from 1300 m producing slightly more heat. The sample from 1400 m released more than twice the smoke yielded by the other samples. Maximum smoke density was highest for the higher altitude samples, and the amount of smoke released varied proportionately with altitude. The mean release density of CO increased abruptly at 1100 m and decreased after that point before an abrupt increase at 1500 m, and that of CO_2 showed almost the same pattern as for CO.

INTRODUCTION

Along the east coast of South Korea, most large–scale forest fires occur during the months of March and April. This season is marked by warm, dry winds that can accelerate the spread of fires. Other contributors to fires in this season include the presence of dry forest fuel (resulting from dry weather conditions), consistent winds, and accumulated organic matter (Kim, 2005). Major controlling factors are local topography (situation and slope gradient), the type, distribution, and density of fuel, and meteorological factors such as humidity and wind velocity. It is difficult to attribute a single factor as the cause of forest fires. Rather, the causes vary, and, in turn, lead to varying behavioral characteristics of forest fires (Lee, 2006).

To predict forest fire occurrence and mitigate associated dangers, country– and region–specific surveys should be carried out to examine the causes and characteristics of forest fires. In addition, studies must also clarify the combustion characteristics of various types of vegetation according to regional topography, weather, and topographic characteristics (Kim *et al*., 2006; Chae *et al*., 2003; Jung *et al*., 2002). To predict the potential hazard a particular fuel represents, and thus develop appropriate technology and systems for hazard management, data from indoor and outdoor experiments on the effects of vegetation distribution and type are needed (Chun *et al*., 2001; Lee, 2004). Recent studies in Korea

have examined the combustion characteristics of forest fuel with the intention of developing dynamic predictions of fire intensity; however, further work is required (Lee *et al*., 2005).

In this study, we examined the different fire characteristics of a typical forest fuel collected at different altitudes. Living leaves of *Pinus densiflora* Sieb. et Zucc. were used as the sample fuel because this species is the most susceptible to combustion in the study area. The moisture content of the leaves was measured before combustion and the characteristics of ignition, fire, and smoke release were measured using an ignition temperature chamber, a cone calorimeter, and a smoke density chamber, respectively.

MATERIALS AND METHODS

1. Site selection
1.1. Study site and fuel
Mt. Taebaek (1567 m) in Gangwon Province was chosen as the study location because its topography and vegetation are typical of the east coast of Korea, where most large–scale forest fires occur. Living leaves of *P. densiflora* were used as the test fuel. This species is highly susceptible to fire and was chosen in order to replicate the conditions of actual forest fires. Seven fuel samples were taken along a hiking trail at intervals of 100 m between altitudes of 900 m to 1500 m. The samples were collected in October, after 5 consecutive days of fine weather conditions.

1.2. Measuring moisture content
Before combustion characteristic tests were conducted, the moisture content of the sample fuel was measured. Moisture content was measured using formula (1) according to ASTM D2016 (American Society for

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Table 1. Experimental conditions of the smoke density chamber and cone calorimeter

Items	Cone calorimeter	Smoke density chamber
Size (mm)	100×100	75×75
Weight (g)	50	10
Heat flux (kW/m²)	50	25
Test time (s)	the time until there is no more weight decrease	1,200
Material condition	Raw	Raw

Testing and Material) (Kim *et al.*, 2004; Shim *et al.*, 1994). A 200–g sample was dried in a 103 °C oven for 24 hours, and was then measured until it reached constant mass. The mean value of three measured values was used as the outcome value. Samples were collected in October, after 5 consecutive fine days. MC (moisture content) is the moisture content ratio [%], W represents the weight of samples before drying [g], and W0 is the weight of dried samples.

$$MC \ (\%) = \frac{W - W_0}{W_0} \times 100 \ (\%) \tag{1}$$

1.3. Combustion characteristic tests

To test the combustion characteristics of living *P. densiflora* leaves with altitude variation, tests on the characteristics of ignition, fire, and smoke release were conducted. To analyze the characteristics of ignition, ignition temperature (IT), time to ignition (TTI) and time to flameout (TTF) were measured. For an analysis of fire characteristics, total heat release (THR) and mean heat release rate (mean HRR) were used, and for the characteristics of smoke release, total smoke release (TSR), maximum smoke density (max. Ds), and smoke temperature (Ts) were measured. The mean release densities of the combustion products CO and CO_2 were also analyzed.

2. Methods
2.1. Analysis of ignition characteristics

To analyze ignition characteristics, non–flame IT was measured using an IT chamber (model number KRS–RG–9000; Kuramochi Co., Japan; Hong *et al.*, 1992). The time for flash ignition, when fuel was exposed to radiation, was recorded using a cone calorimeter. Flame close time, namely, the time when the fire was extinguished naturally, was measured and after–flame time was analyzed simultaneously. The presence or absence of a flame at flash ignition was recorded, as judged by the naked eye.

2.2. Analysis of fire characteristics

To examine fire characteristics, a dual cone calorimeter chamber (ISO 5660–1, 2002) of FTT Co., England was used to analyze the mean HRR. The experiment ended when the sample stopped decreasing in weight, and this value was chosen as the output value. The mean value of three replicates was used as the outcome value. The THR was calculated based on the accumulated value by integrating the heat release rate, represented by a function of time, per its sample's surface area. The mean

HRR was calculated by dividing the THR by the given amount of time. The experimental conditions are presented in Table 1.

2.3. Analysis of smoke release characteristics

To analyze the characteristics of smoke release, a smoke density chamber (ASTM E 662, 2003) and cone calorimeter (FTT Co.) were used. TSR and Ts were measured with the cone calorimeter, and smoke density was analyzed using the smoke density chamber. Since TSR measured by the cone calorimeter is the total smoke occurrence per unit area according to ISO 5660–2 (ISO 5660–2, 2002), and as smoke occurs in proportion to area, a standard value related to the area was used.

The total smoke occurrence rate (m²) was the value integrated by the time of smoke release (m²/s) in the related section. Ts was measured using a thermocouple when the smoke had passed through a 0.5⁻mW helium–neon laser in a duct. For the measurement of smoke density, a smoke density chamber was used, applying a vertical test of non–flaming. The mean value of three replicates was used as the outcome value. Experimental conditions are presented in Table 1.

RESULTS AND DISCUSSION

1. Moisture content

The living leaves of *P. densiflora* from the various altitudes contained between 148% and 177% moisture (Fig. 1). The curve in Figure 1 shows that the moisture content of the leaves increased with altitude up to 1100 m after which the moisture content decreased as the altitude increased. The results of the moisture content measurements were as follows. 152.01% for the
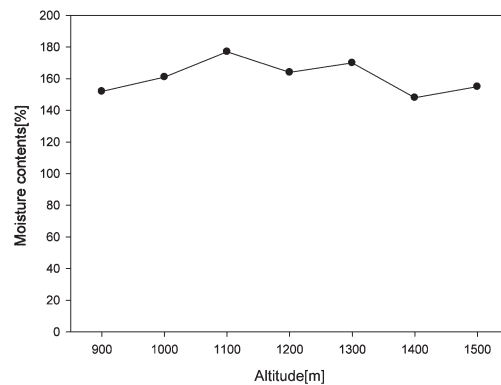

Fig. 1. Moisture content (%) of living leaves of *P. densiflora* by altitude.

Table 2. Ignition characteristics of living leaves of *P. densiflora* from different altitudes

Items	Altitudes (m)						
	900	1000	1,100	1,200	1,300	1,400	1,500
Time to ignition (s)	48	not recorded	not recorded	not recorded	63	not recorded	not recorded
Time to flameout (s)	52	not recorded	not recorded	not recorded	65	not recorded	not recorded
Ignition temperature (°C)	308	308	310	310	308	305	310

sample for 900 m; 161.20% for 1000 m; 176.80% for 1100 m; 164.38% for 1200 m; 169.62% for 1300; 147.54% for 1400 m, and 154.83% for 1500 m.

2. Ignition characteristics

Table 2 shows the variation in ignition characteristics for live *P. densiflora* leaves from different altitudes. The ignition temperature shown in Table 2 is the non–flame ignition temperature and is relatively consistent at 305~310 °C. The times to ignition and flameout were recorded for the 900 m and 1300 m samples, but not at the other altitudes because, as with the cone calorimeter, only flame ignition times, not non–flame ignition times, were recorded in this study. Notably, although flame ignition was only initiated at 900 m and 1300 m, the flames disappeared after 7 and 8 s, respectively.

As shown in Figure 4, the sample from 1400 m released a significant amount of smoke, which indicates non–flame ignition. The samples taken at 900 m and 1400 m which had relatively low moisture content, revealed different characteristics of ignition. Hence, there appeared to be a difference between ignition characteristics (i.e., flame or non–flame ignition) by altitude, but no consistent trend was shown. This could perhaps relate to the fact that, not only does leaf moisture content

change with altitude, but so does the nature of foliage tissue; that is, changes in cell gaps and needle components may also vary with altitude and thus affect combustion (Yim, 2007).
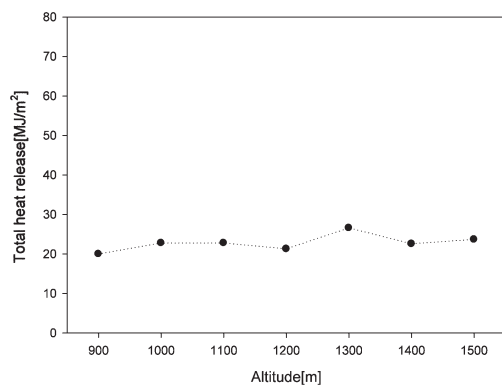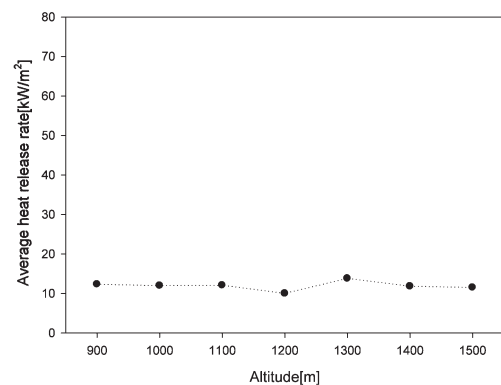
3. Fire characteristics

Total heat release was between 20 and 27 MJ/m² (Fig. 2) and the mean heat release rate was between 12 and 14 kW/m² (Fig. 3). This suggests that there is little significance in the relationship between heat release and altitude. The sample taken at 1300 m showed a slightly higher rate of heat release than the other samples, which can be attributed to its flame rather than non–flame ignition. The sample from 1200 m showed the lowest heat release rate. The sample from 900 m experienced flame ignition, but this did not affect heat release. The outcome values are given in Table 3.

4. Smoke release
4.1. Total smoke release, maximum smoke density, and smoke temperature

Figure 4 shows the curve for the total smoke release of samples weighing 50 g. The sample taken at 1400 m released 347.23 m²/m² of smoke, which is more than double the amount of smoke released by each of the other

Fig. 2. Total heat release from living leaves of *P. densiflora* from various altitudes.

Fig. 3. Heat release rate of living leaves of *P. densiflora* from various altitudes.

Table 3. Characteristics of flame spread in living leaves of *P. densiflora* with change in altitude

Items	Altitudes (m)						
	900	1,000	1,100	1,200	1,300	1,400	1,500
Average HRR (kW/m²)	12.35	12.01	12.1	10.03	13.84	11.87	11.52
Total heat release (MJ/m²)	20	22.8	22.8	21.3	26.6	22.6	23.7

samples. The sample taken from 900 m had a maximum smoke density of 99.52 Ds at 1200 s (Fig. 5). The results then show no significant difference until the sample from 1400 m, which had the maximum smoke density (143.94 Ds at 937 s). The highest maximum smoke density, 144.96 Ds at 869 s, was yielded by the 1500 m sample, which also released the most smoke over the shortest time interval.

This would suggest a positive correlation between altitude and the maximum smoke density value of the fuel. This is significant because it would imply that when
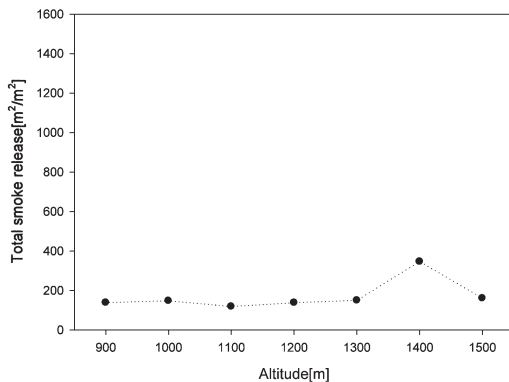

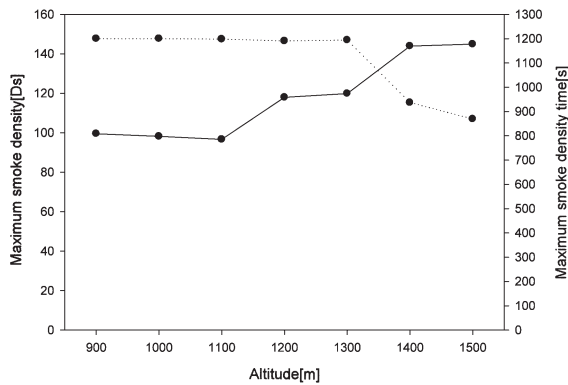**Fig. 4.** Total smoke release from living leaves of *P. densiflora* from various altitudes.

Fig. 5. Smoke density from living leaves of *P. densiflora* from various altitudes.
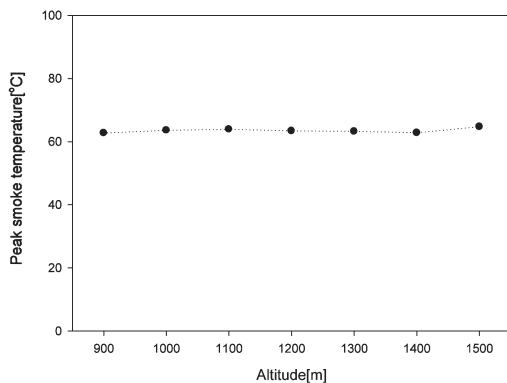

Fig. 6. Smoke temperature from living leaves of *P. densiflora* from various altitudes.

forest fires erupt at higher altitudes, smoke release will reduce visibility much more than in fires at lower altitudes. Furthermore, maximum smoke density was reached in a short time, meaning that evacuation must take place rapidly after a fire breaks out. Figure 6 shows the peak smoke temperature. For smoke temperature by altitude, the range of maximum Ts was 63–65 °C, with no variation according to altitude. Table 4 presents the outcome values.

4.2 CO and CO_2

The mean release density of CO rose abruptly at 1100 m (Fig. 7). The mean release density then decreased with higher altitude before a sudden increase at 1500 m. Although the CO densities of the samples taken at 900 m and 1300 m were relatively low, they did exhibit flame ignition, whereas the mean release density of CO was higher for the samples taken at high altitude which had non–flame ignition. The mean release density was high in the latter type of ignition because incomplete combustion causes more CO to be released. The mean release density of CO_2 showed almost the same result as that of CO, with differences in density by altitude. The outcome values are presented in Table 5.

The combustion products, CO and CO_2, were produced at high temperatures, from the fuel's main component, cellulose. Patterns in the release of these combustion products are closely related to the conditions of combustion, such as the composition of the fuel, the heating temperature, and the fuel supply. Release of CO_2 may also have other deleterious effects, such as contributing to the greenhouse effect. Accordingly, the density and toxicity of smoke have to be considered independently from other factors (Lee, 1993).

CONCLUSIONS

This study conducted a series of experiments on living leaves of *P. densiflora*, a species that is particularly susceptible to fire. The study aim was to compare the combustion characteristics of fuel at different altitudes. The conclusions can be summarized as follows:

1) Moisture content of the *P. densiflora* samples ranged from 148% to 177% and generally increased with altitude until 1100 m, after which moisture content
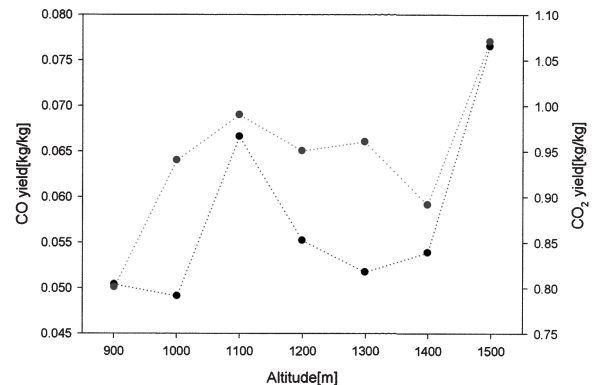

Fig. 7. CO and CO_2 yields from living leaves of *P. densiflora* from various altitudes.

Table 4. Characteristics of smoke release from living leaves of *P. densiflora* collected at different altitudes

Items	Altitudes (m)						
	900	1,000	1,100	1,200	1,300	1,400	1,500
Total smoke release (m^2/m^2)	138.75	147.93	118.99	138.27	150.22	347.23	160.89
Peak Smoke temp. (°C)	62.74	63.57	63.9	63.41	63.27	62.82	64.73
Max. Smoke density (Ds)	99.52	98.2	96.68	117.96	119.89	143.94	144.96
Max. Ds time	1200	1200	1198	1191	1194	937	869

Table 5. Concentrations of combustion gases from living leaves of *P. densiflola* collected at different altitudes

Items	Altitudes (m)						
	900	1,000	1,100	1,200	1,300	1,400	1,500
Average CO yields	0.0503	0.049	0.0666	0.0551	0.0516	0.0537	0.0765
Average CO_2 yields	0.8	0.94	0.99	0.95	0.96	0.89	1.07

decreased with elevation. However, the samples from 900 m and 1400 m both had low moisture content, thus contradicting the apparent relationship.

2) There was no significant difference between the ignition characteristics of leaves sampled at different altitudes, with non–flame temperature ranging from 305 to 310 °C. Flame ignition occurred in the samples from 900 m and 1300 m, while the sample taken at 1400 m showed non–flame ignition with large amounts of smoke released, indicating a difference in flame and non–flame ignition by altitude.

3) Total heat release ranged from 20 to 27 MJ/m^2 and the mean heat release rate ranged from 12 to 14 kW/m^2. No relationship was found between heat release and altitude. The heat release rate from the 1300 m sample was slightly higher than that from the other samples. This can be attributed to the occurrence of flame ignition at this altitude.

4) The sample from 1400 m released 347.23 m^2/m^2 smoke, which was twice as much as the release rates of the other samples. The maximum smoke density increased with sample altitude because of the large amount of smoke released at the beginning of combustion. This suggests that more smoke is released over a shorter time interval in proportion with increasing altitude.

5) The mean density of CO released during combustion increased abruptly at 1100 m and decreased after that point before an abrupt increase at 1500 m. However, the samples taken at 900 m and 1300 m had low CO densities with flame ignition. The mean release density of CO_2 showed almost the same pattern as for CO, with considerable difference by altitude.

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