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Vulnerability of *Pinus densiflora* to forest fire based on ignition characteristics

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In Korea, man-caused forest fires are known originate primarily in coniferous forests. We have hypothesized that the vulnerability of *Pinus densiflora* forests is principally a consequence of the ignition characteristics of the species. To assess this hypothesis, we conducted two combustion experiments using fallen leaves with a reference species, *Quercus variabilis*. In the first experiments, in which a cigarette was employed as a primary heat source for the initiation of a forest fire, the *Pinus* leaves caught fire significantly faster (1′1″ at *Pinus*, 1′31″ at *Quercus*, $P < 0.001$), and ignition proceeded normally. *Quercus* leaves, on the other hand, caught fire but did not ignite successfully. In the second set of experiments utilizing different moisture contents and fuel loads, the maximum flame temperature of the *Pinus* leaves was significantly higher (421°C at *Pinus*, 361°C at *Quercus*, $P < 0.001$) and the combustion persisted for longer than in the *Quercus* leaves (8′8″ at *Pinus*, 3′38″ at *Quercus*, $P < 0.001$). The moisture contents of the leaves appeared to be a more important factor in the maximum temperature achieved, whereas the most important factor in burning time was the amount of fuel. Overall, these results support the assumption that *Pinus* leaves can be ignited even by low-heat sources such as cigarettes. Additionally, once ignited, *Pinus* leaves burn at a relatively high flame temperature and burn for a prolonged period, thus raising the possibility of frequent fire occurrences and spread into crown fires in forests of *P. densiflora*.

Key words: burning time, cigarette, forest fire, ignition characteristics, maximum flame temperature, *Pinus densiflora*, *Quercus variabilis*, vulnerability

INTRODUCTION

Fires require three factors: fuel, oxygen, and heat (Chandler et al. 1983). Litter, branches, and woody debris are the main fuels implicated in forest fires. In particular, fine fuels such as dried fallen leaves and small branches are regarded as an important factor in the ignition stage (Chandler et al. 1983, Haessler 1989). Once ignited, forest fires move into the spread stage, evidencing a variety of behaviors and intensities depending on the amount of fuel, as well as meteorological or geographical factors (Burgan and Rothermel 1984).

Lee et al. (2005) analyzed forest fire records across the country, and concluded that the initial ignition of forest fires most frequently occurs in coniferous forests (69%), followed by mixed forests (17%) and broadleaf forests (14%), respectively. In this regard, three possibilities have been raised as to why forest fires occur primarily in coniferous forests. First, coniferous forests are characterized by a wide spread, and thus they are very likely to be exposed to people, resulting in a higher possibility of man-caused fires. Second, coniferous trees exist principally at lower elevations near villages or memorial parks, which are easily accessed by humans. Finally, the ignition char-

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acteristics of coniferous trees in Korea are responsible to their vulnerability of fire.

It has been reported previously that 42% of domestic forests are coniferous forests, while 26% are broadleaf forests. In the East Coast regions (Goseong, Yangyang, Sokcho, Gangneung, Donghae, and Samcheok) of Gangwon province, where large forest fires most frequently occur, the forest composition is as follows: 38% coniferous, 29% broadleaf and other forests (Korea Forest Service 2009). Coniferous forests cover a wider area than broadleaf forests. However, the ratio of forest fires in coniferous forests is 69%, which is far higher than their proportions relative to other forest types; this cannot be sufficiently explained for the first reason listed above, although it is true that more coniferous forests are distributed throughout regions of lower elevation. The pre-fire vegetation of the East Coast fires region in 2000 was characterized by a relatively high frequency of *Pinus densiflora* forests, the most dominant forest type among coniferous forests, at lower elevations (Choung et al. 2004). This may, to some degree, be related to that region's general susceptibility to fire. Clearly, coniferous trees are more likely to encounter heat sources; however, if the fuel cannot be ignited, no fire can start. Thus, greater access to forests by humans is not, in and of itself, a satisfying explanation for the increased vulnerability of coniferous forests to fire.

Therefore, the frequent occurrences of fire in coniferous forests are assumedly attributable to the ignition characteristics of coniferous trees at the ignition stage. *P. densiflora* harbors a variety of volatile substances, such as resins and terpene, in its timber, cambium, leaves, and branches (Song and Kim 1994). Additionally, its organs contain a large caloric content (Park et al. 2007) which potentially increase firing possibility and allow for prolonged combustion.

In Korea, most fires have been identified as man-caused fires. Forty nine percent of fires are reported by people visiting the graves of family members in mountains or memorial parks which are commonly located in lowland mountainous regions. Thus far, 10% of fires were identified as being directly induced by cigarettes. However, the actual percentile is assumed to be substantially higher than reported. Kim et al. (1994) demonstrated that the coniferous species, *P. rigida* and *Larix leptolepis,* catch fire more quickly than the broadleaf species, *Quercus acutissima,* when employing cigarettes as a heat source. However, the responses of *P. densiflora* and *Q. variabilis* to cigarettes have yet to be evaluated, even though these are the predominant tree species in the relevant areas.

The principal objective of this study was to prove that the ignition characteristics of *P. densiflora* forests are one of the major factors in their susceptibility to fire. We compared the ignition characteristics of *P. densiflora* with *Q. variabilis,* which was utilized as a reference species. *Q. variabilis* either coexists, or forms pure stands in the neighbourhood of *P. densiflora* stands in Korea. This study involved two related experiments. The first of these experiments was conducted to compare the possibility of the firing and ignition of *Pinus* and *Quercus* leaves with different moisture contents, using a cigarette as a heat source. The second experiment involved the measurement of maximum burning temperatures and burning time of *Pinus* and *Quercus* leaves of differing moisture contents and fuel loads. Firing is defined as the process by which a substance catches fire after exposure to an ignition source. In firing, smoke, but no flame, is produced. If the ignition source is removed, the substance will not continue to burn. Ignition, however, is defined as the production of flames subsequent to firing. A successfully ignited substance continues to burn even when the ignition source is removed.

MATERIALS AND METHODS

Collecting fuel source

Fallen leaves were employed as a fine fuel source, as it evidences higher combustibility and can be readily ignited. In our experiment, fallen leaves of *P. densiflora* and *Q. variabilis* were collected from the forests of Seongsan-myeon and Sacheon-myeon, Gangneung-si, Gangwon-do, respectively, in the summer and autumn of 2008. Both *P. densiflora* and *Q. variabilis* forests largely exist as pure stands consisting of trees in their thirties. The collected leaves were dried in a drying oven at 60°C until their weight no longer changed.

Combustion experiment

Assuming that a cigarette is a primary heat source in forest fires, we conducted firing and ignition experiments with fallen leaves with differing moisture contents. The moisture contents were adjusted by spraying water evenly onto 20 g of dried leaves at 0%, 5%, and 10% (v/w) in plastic bags. The plastic bags were kept tight and were shaken until the combustion experiments began the next day. The moisture contents ratios were established on the basis of the moisture contents of fine fuels in *P. densiflora* and *Q. variabilis* forests through the fall and

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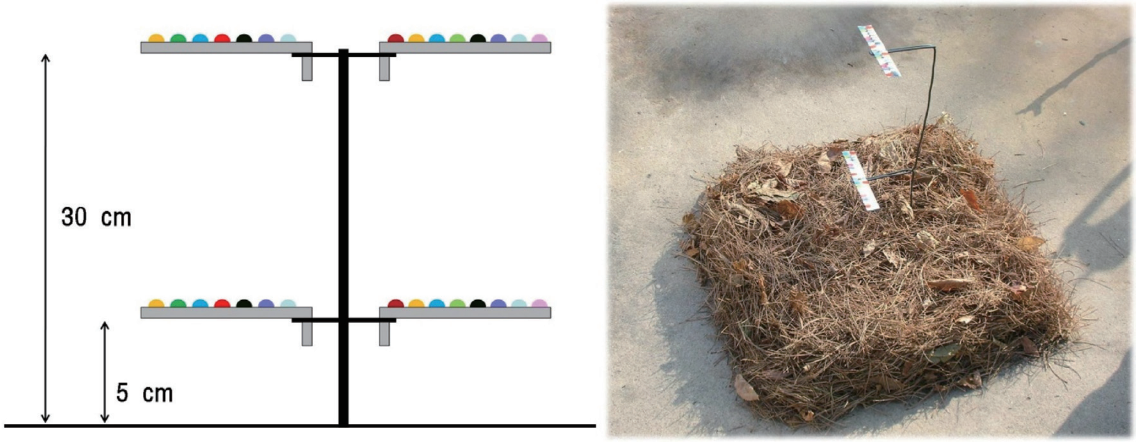

Fig. 1. Thermocolor pyrometer modified from Graham and McCarthy (2006).

spring seasons in the field, as demonstrated previously by Seo (2010). Firing and burning time were measured by the insertion of a cigarette 1 cm into a 10 cm × 10 cm cluster of leaves. We repeated the same test five times for each of the moisture contents. These experiments were conducted in an open area on June 14, 2009. Wind speed was in the range of 0-1.2 m/s, and the air temperature and relative humidity were 21.5-23.9°C and 54.6-63.1%, respectively.

In the second experiment, we burned leaves with differing moisture contents and quantities of fuel, and then determined the maximum burning temperature and burning time. The moisture contents were adjusted to 0%, 5%, and 10% in the same fashion as was established for the above test. Both 300 g and 600 g of the 50 cm × 50 cm cluster of leaves (1,200 g and 2,400 g per m^2, respectively) were set on the basis of the amount of leaves in a natural setting, according to Seo (2010), on the ground. A torch was then used to set fire to the leaves. To measure the temperature of the flame, we designed a thermocolor pyrometer modified from the research of Graham and McCarthy (2006). The thermocolor pyrometer consists of 15 different Tempilaq° G liquid paints on aluminum tags with various melting points (79, 107, 135, 163, 191, 218, 246, 274, 316, 371, 427, 482, 538, 593, and 649°C). Two of the thermocolor pyrometers were set at heights of 5 cm and 30 cm on the right and left (Fig. 1). The maximum burning temperature was determined by checking the melted paint on the right and left aluminum tags. We measured the burning time when the leaves had burnt completely. The second experiments were repeated four times in the open area at two different days, April 18 and May 30, 2009. On April 18, the wind speed was in a range of 1.9-2.8 m/s, and the air temperature and relative humidity were 21.7-25.5°C and 13.4-21.1%, respectively. On May 30, the wind speed was in a range of 0-1.2 m/s, and the air temperature and relative humidity were 16.4-22.4°C and 33.4-54.4%, respectively. The results from the two different days were averaged.

Statistical analysis

We used an analysis of variance to assess significant differences between species, moisture contents and fuel loads on firing time, maximum temperature, and burning time. Mean differences were analyzed via Bonferroni's *post hoc* test. Multiple regression analysis was employed to determine the relative effects of burning temperature and time. SYSTAT ver. 10 (SPSS Inc., Chicago, IL, USA) software was employed to process the results of the analyses.

RESULTS AND DISCUSSION

Firing and ignition by cigarette

Pinus leaves were set on fire with a cigarette, after which ignition proceeded normally, whereas *Quercus* leaves caught fire but did not proceed to full ignition (Fig. 2). *Pinus* (average 1′1″) appeared to catch fire more quickly than *Quercus* (average 1′31″). The difference between the two species was statistically significant ($F = 28.9$, $P < 0.001$) (Table 1). With increases in the moisture contents, more firing time was required. *Pinus* leaves caught fire 1.8 times and 1.2 times more quickly than *Quercus* leaves when the moisture contents were 0% and 10%, respectively. Moisture content appeared to affect the firing time

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significantly ($F = 4.1$, $P < 0.05$) (Table 1). This was clearer in the *Pinus* leaves, but no significant trend was noted in the *Quercus* leaves (Fig. 2). Based on the moisture contents, the firing time of the *Pinus* leaves was measured at an average 5′42″ for 0%, 7′32″ for 5%, and 9′10″ for 10%.

Seo (2010) monitored the varying moisture contents of fine fuel from *P. densiflora* and *Q. variabilis* forest stands in Gangneung-si, Gangwon-do over the year. The moisture content appeared to decline significantly after summer, and was lowest in the spring. In April, the average moisture content of the fine fuel was 7.2% in *P. densiflora* stands and 6.7% in *Q. variabilis* stands. The moisture contents between *P. densiflora* and *Q. variabilis* stands did not differ significantly. By adopting the moisture content of April to the results of this study, it can be assumed that it would require approximately 8′15″ for a *P. densiflora* forest stand to be ignited by cigarettes. April is the most active fire season in Korea.

Such results support the hypothesis that cigarette butts thrown in the forest during the spring season can cause fine fuels to catch fire, and may possibly ignite forest fires in *P. densiflora* forests. The reason that *P. densiflora* can so readily catch fire may involve the volatility of its resins or terpenes (Song and Kim 1994). Additionally, coniferous trees evidence a higher surface area/volume ratio due to their shape (Hely et al. 2000) such that coniferous trees like *P. densiflora* are exposed to larger surface-to-ignition sources than other broadleaf trees such as *Q. variabilis* for the same volume. Kim et al. (1994) also noted that coniferous forests (pitch pine, larch, etc.) caught fire for shorter periods of time than broadleaf trees (eg. *Q. acutissima*) when exposed to a burning cigarette. Furthermore, Lee et al. (2009) reported previously that fallen leaves containing lower moisture contents caught fire for shorter periods of time than live leaves, because their natural burning temperature is lower.

Maximum burning temperature and burning time

We burned the leaves of *Pinus* and *Quercus* with various amounts of fuel and moisture contents in order to determine the maximum burning temperature and burning time of these materials. *Pinus* leaves at a height of 5 cm evidenced an average burning temperature of 421°C, which is approximately 1.8 times the average burning temperature of 329°C at a height of 30 cm (Fig. 3). The burning temperature of *Quercus* leaves at a height of 5 cm was 361°C on average, which is approximately 1.5 times the average burning temperature of 239°C measured at a height of 30 cm.

Both species appeared to have the highest burning temperature with the lowest moisture contents, and the burning temperature increased as the quantity of fuel increased as well. *Pinus* leaves at a height of 5 cm had the highest average burning temperature of 473°C at a moisture content of 0%, and an average of 441°C at 5%

Table 1. Analysis of variance for the effects of firing time (two-way), maximum temperature, and burning time (three-way)

	Source	d.f	*N*	Mean square	*F*-ratio	*P*-value
Firing time	Species	1	24	5,551.042	28.889	0.001
	Moisture	2	24	790.292	4.113	0.034
	Error	18	24	192.153		
Maximum temperature at 5 cm	Species	1	45	65,935.951	13.965	0.001
	Moisture	2	45	21,307.734	4.513	0.019
	Fuel load	1	45	23,765.438	5.033	0.032
	Error	33	45	4,721.593		
Maximum temperature at 30 cm	Species	1	46	235.930	0.037	0.850
	Moisture	2	46	38,410.704	5.951	0.006
	Fuel load	1	46	14,103.719	2.185	0.149
	Error	34	46	6,454.167		
Burning time	Species	1	44	646,287.019	104.424	0.000
	Moisture	2	44	28,599.508	4.621	0.017
	Fuel load	1	44	133,700.252	21.603	0.000
	Error	32	44	6,189.076		

Interaction terms, which are not significant, are not shown.

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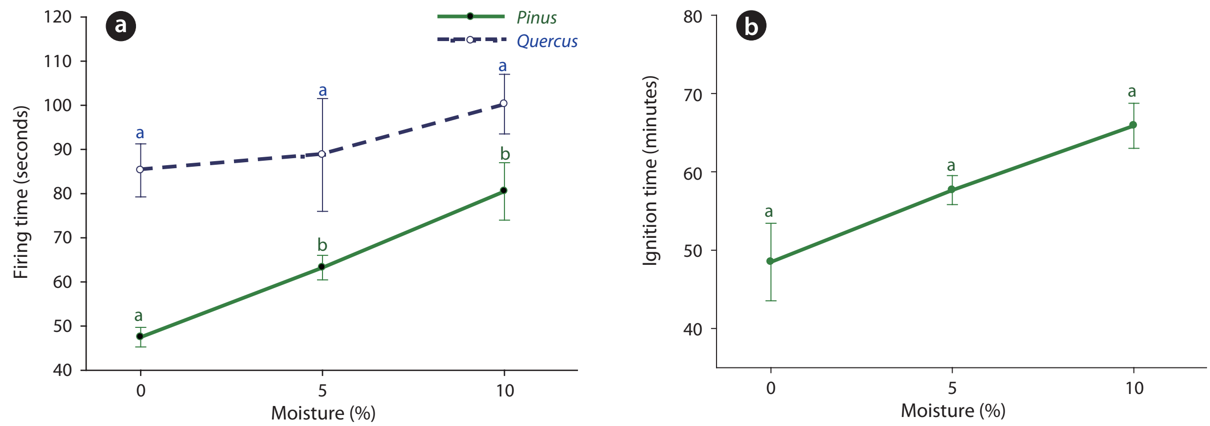

Fig. 2. Firing (a) and ignition time (b) of *Pinus* and *Quercus* leaves by cigarette. Average ± 1 standard error is given (N = 5). Different letters by Bonferroni *post-hoc* test indicate the significant mean difference between moisture conditions within species.

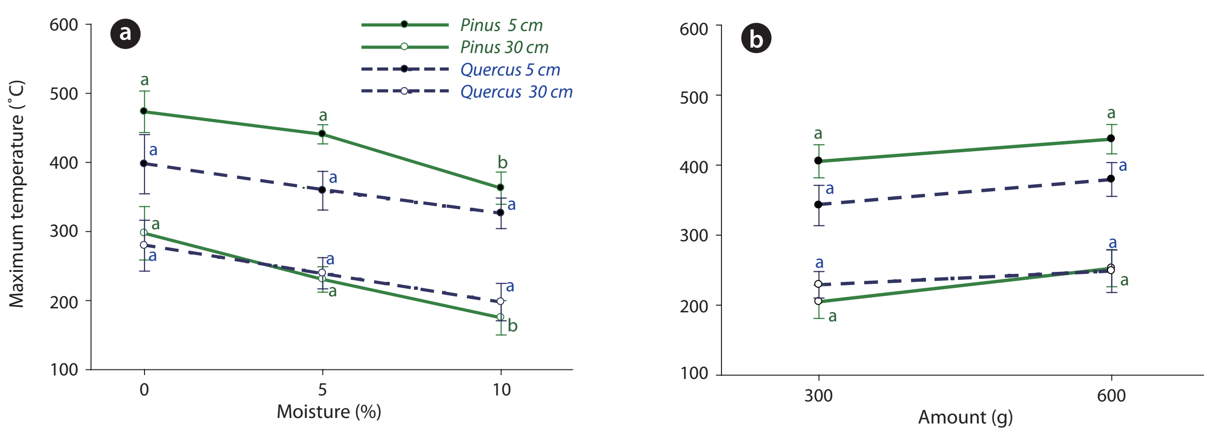

Fig. 3. Maximum burning temperature of *Pinus* and *Quercus* leaves measured at two heights (5 cm and 30 cm) according to different fuel moisture contents (a) and fuel loads (b). Average ± 1 standard error is given (N = 4). Different letters by Bonferroni *post-hoc* test indicate the significant mean difference between treatments within species.

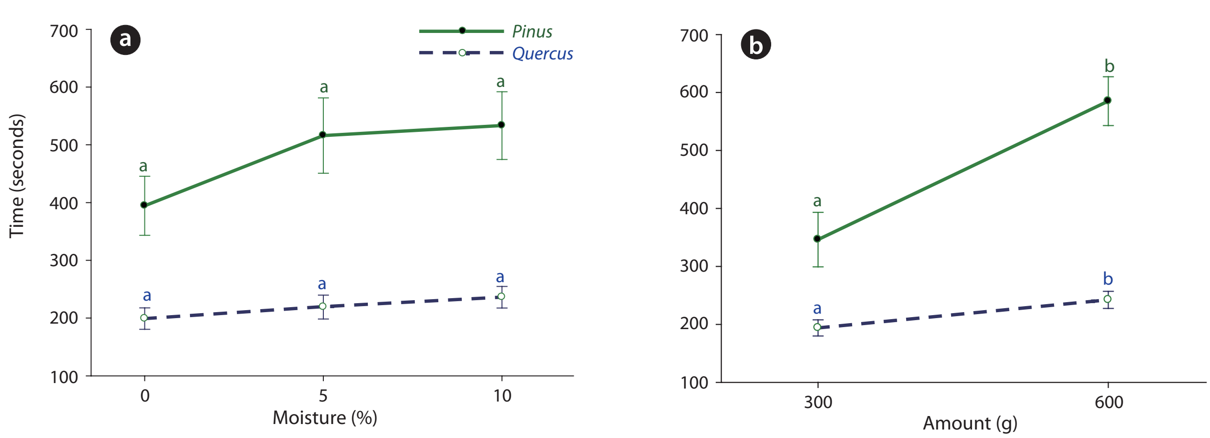

Fig. 4. Burning time according to different fuel moisture contents (a) and fuel loads (b). Average ± 1 standard error is given (N = 4). Different letters by Bonferroni *post-hoc* test indicate the significant mean difference between treatments within species.

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and an average of 363°C at 10% (apparently the lowest temperature in the tested ranges). When the quantity of *Pinus* leaves was 600 g at a height of 5 cm, the burning temperature was an average of 437°C, which is approximately 1.1 times the average of 405°C measured with a mass of 300 g.

According to the analysis of variance with the maximum burning temperatures between two species for various moisture contents and fuel amounts (Table 1), we noted that the maximum temperature of *Pinus* at a height of 5 cm was significantly higher than that of *Quercus* ($F = 14.0$, $P < 0.001$). However, no significant differences were noted between the two species at a height of 30 cm. The maximum temperature at various moisture contents differed significantly at heights of 5 cm and 30 cm, whereas the maximum temperature for different fuel loads was significant only at a height of 5 cm (Table 1). At a height of 30 cm, flames occasionally failed to reach the thermocolor pyrometer due to the effects of wind, which likely resulted in substantial deviation. The results of multiple regression analysis showed that moisture contents are more important than the quantity of fuel for the maximum temperature at heights of 5 cm ($F = 8.253$, $P < 0.01$) and also 30 cm ($F = 8.064$, $P < 0.001$).

The burning time of *Pinus* leaves appeared to be influenced by moisture contents or by the quantity of fuel (Table 1). On the other hand, *Quercus* leaves did not appear to be affected. At a moisture content of 0%, the burning time of *Pinus* was an average of 6′35″, and was measured at an average of 8′23″ and 8′53″ at 5% and 10%, respectively (Fig. 4). The average burning time of *Pinus* was 8′8″ whereas the average of *Quercus* was 3′38″. Accordingly, *Pinus* burned approximately 2.2 times longer than *Quercus*. Such differences are statistically significant ($F = 104.4$, $P < 0.001$) (Table 1).

In particular, with increases in the quantity of fuel, *Pinus* leaves required longer burning time. That is, 600 g of *Pinus* leaves required 9′38″ to burn, which is approximately 1.5 times longer than the 6′16″ average determined with 300 g of leaves. To enhance the burning process, more space between leaves is required, as this allows for oxygen to be provided to the flames. However, *Pinus* leaves are dense and needle-shaped, which may keep oxygen outside the leaf mass. This may cause *Pinus* to burn more slowly. Furthermore, *Pinus* leaves have a higher caloric content, at 5,231 cal/g, than *Quercus* leaves, at 4,850 cal/g (Park et al. 2007). This appears to be attributable to the resin components of *P. densiflora* trees (Song and Kim 1994, Aerts 1997). According to the results of multiple regression for the effects of various moisture contents and fuel quantities on burning time, it appears that the amount of fuel is a more important factor than the moisture contents at a height of 5 cm ($F = 4.729$, $P < 0.014$). In the spring season, *Q. variabilis* forests contain approximately 1.3 times as much fine fuel as *P. densiflora* forests (Seo 2010).

Nevertheless, the fact that forest fires occur less frequently in broadleaf forests such as *Quercus* forests is believed to be attributable to the difficulty of initial ignition of *Quercus* leaves by a cigarette, as was demonstrated in our test with the leaves of *Q. variabilis*. With the combination of weather conditions and forest composition in addition to the ignition characteristics of *P. densiflora*, forest fires would be expected to occur more frequently and inflict more severe damage in coniferous forests such as *P. densiflora* forests, than in broadleaf forests.

As a short-term plan, we recommend that specific areas densely forested with *P. densiflora* at lower altitude should be identified as vulnerable fire zones. Public access to these zones should be controlled, particularly in the severely dry spring months. Eventually, *Pinus*-dominated forests will be replaced by mixed forests or broadleaf forests by succession, resulting in greater resistance to heat sources.

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