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Modelling the Probability of Japanese Red Pine Mortality After a Forest Fire in Korea

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We investigated Japanese red pine (*Pinus densiflora* Siebold et Zuccarini) mortality that resulted from a 17,097 ha forest fire that occurred in eastern Korea in April of 2000. We developed a logistic regression model that relates the probability of tree mortality to diameter at breast height (DBH) and height of stem blackening (HSB) and found the probability of tree mortality increased as the HSB increased and DBH decreased. We compare those results with stem mortality models developed for Scots pine (*Pinus sylvestris* L.) in Sweden and Eastern white pine (*Pinus strobes*, L.) in Canada and discuss the need for methodologies that can be used to develop comparable models.

INTRODUCTION

The forested area of the Republic of Korea in 2008 was approximately 6.4 million ha, roughly 64% of its total land area (Korea Forest Service 2008). Most of the forested area is located in the mountainous areas of the country and the predominant tree species is Japanese red pine (*Pinus densiflora* Siebold et Zuccarini). Most Korean forest fires are caused by people and from 1999–2008, a total of 4,971 forest fires (479 fires per year) burned 36,355 ha (3,635 ha per year) (Korea Forest Service 2008). More than 60 percent of those fires occurred during the dry and windy spring and fall seasons when many people visit forests to gather wild vegetables or for recreational purposes.

This paper reports the results of our investigation of Japanese red pine mortality caused by a forest fire that burned 17,097 ha in eastern Korea during the month of April, 2000. We used logistic regression analysis methods to develop an empirical relationship between the post–fire mortality of Japanese red pine trees and fire intensity and tree characteristics. We then compare our model with published mortality models for Scots pine (*Pinus sylvestris* L.) in Sweden and Eastern white pine (*Pinus strobes*, L.) in Canada and discuss the need for methodologies that can be used to develop comparable models.

METHODS

A people–caused forest fire and associated spot fires that ignited in the Samchuck city study area burned 17,097 ha from April 7, 2000 to April 14, 2000 (Fig. 1).

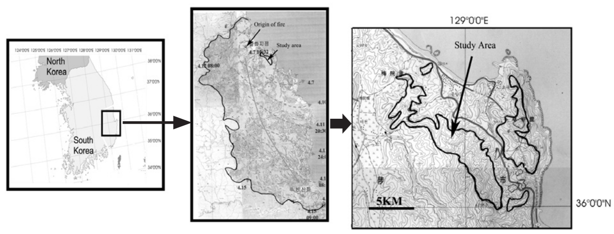

Fig. 1. Map of the fire that burned in the Samchuck city study area in 2000 (Korea Forest Service 2001b).

The maximum wind speed and minimum relative humidity recorded at Samchuck city were 8.5 km/h and 15%, respectively. The average fire spread rate was reported to be 0.3 km/h (Korea Forest Service 2001b). The burned area contained softwood stands (11,424 ha), hardwood stands (2,851 ha), and mixed–wood stands (2,822 ha). The conifer stands contained Japanese red pine (*Pinus densiflora* Siebold & Zucc), Korean Pine (*Pinus koraiensis* Siebold & Zucc.), Pitch Pine (*Pinus rigida* Mill.) and Larch (*Larix leptolepis* (Y. Z. Qi & Zucc.) Gordon). The hardwood stands contained Sawtooth Oak (*Quercus acutissima* Carruth. for. acutissima), Mongolian Oak (*Quercus mongolica* Fisch. ex Ledeb.), Cork Oak (*Quercus variabilis* Blume), Japanese Chestnut (*Castanea crenata* Y. Z. Qi & Zucc.), Japanese Alder (*Alnus japonica* (Thunb.) Steud) (Korea Forest Service 2003). The most common softwood species in the study area was Japanese red pine which is flammable and easily killed by fire.

The post–fire field observations reported in this study were recorded in August of 2001, 16 months after the fire occurred. A total of 26 plots were established on a ridge that ranged from 300 to 800 m elevation at spacing of roughly 20 to 30 meters between plots. Most of the stands in this area were predominately Japanese red pine stands and each sample plot was either 15×15 m (if it was located in a relatively flat area) or 10×10 m (if it was in rough terrain). Most of the stands ranged from 20 to 50 years of age on gray brown forest soils (Korea

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Forest Service 2001) and exhibited a range of fire damage.

All the Japanese red pine trees in the 26 plots were examined and classified as either living or dead based on crown conditions using the following subjective classification rule – any tree that had shed all of its needles or contained only brown needles was classified as being dead. Any trees that had less than 1% or more of its green needles was classified as being dead and any tree that had 1% or more of its needles green was classed as being alive.

Beverly and Martell (2003) summarized the results of many studies that describe how logistic regression models have been used to relate post–fire tree mortality to a wide range of surrogate measures of fire intensity including crown scorch height, stem char height and crown volume scorched. They noted that many definitions of stem char–related surrogate measures of fire intensity have appeared in the post–fire mortality literature and they used the term "height of stem blackening" (HSB) to distinguish the measured "maximum height of stem blackening" which they used as a surrogate measure of fire intensity from the many stem char–related measured that have been described in the literature. Following Beverly and Martell (2003), we also used HSB as a surrogate measure of fire intensity. The height, diameter at breast height and HSB of all the Japanese red pine in the plots were measured and recorded and the results are summarized by plot in Table 1.

Like Beverly and Martell (2003), we used logistic regression techniques to model the probability of Japanese red pine mortality as a function of DBH (cm) and HSB (m). Our dependent variable was the status of the tree (1 if dead and 0 if alive) and we used SPSS 12 for Windows to estimate the model parameters. We then compared our results with those published for Scots pine in Sweden (Linder *et al.*, 1998) and Eastern white pine in Canada (Beverly and Martell, 2003).

RESULTS

Mortality

There were a total of 179 live and 257 dead Japanese Red Pine trees on the 26 study plots, an aggregate mortality rate of 60% (Table 1). Figure 2 illustrates that on average, the dead trees had a smaller DBH and a higher HSB than the live trees. The average DBH of the live trees was 17.7 cm and average DBH of the dead trees was 12.5 cm. The average HSB was 1.4 m on the live trees and 2.5 m on the dead tree. Fallowing McHugh and (2003),

Table 1. Summary of the data collected on the study plots that were sampled in August of 2001

Plot	Slope (degrees)	Aspect	Fire spread direction	Trees /ha	Live trees				Dead trees			
					Number of trees	Average height (m)	Average DBH (cm)	Average HSB (m)	Number of Trees	Average height (m)	Average DBH (cm)	Average HSB (m)
1	20	N	SE	1800	13	10	21	1.4	5	9.7	19.6	3.5
2	40	E	SE	1900	7	13	26	1.2	12	8.5	13.7	2.6
3	20	E	W	1600	–	–	–	–	16	16.2	22.0	15.2
4	45	N	N	1100	–	–	–	–	11	10.0	18.9	4.1
5	30	E	NW	1800	–	–	–	–	18	7.2	11.0	3.1
6	30	S	E	1300	–	–	–	–	13	9.7	14.6	4.6
7	46	SW	N	1500	–	–	–	–	15	7.9	14.2	3.8
8	40	W	W	1500	6	14	22	2.1	9	9.1	14.3	2.6
9	35	N	S	900	–	–	–	–	9	10.7	20.4	4.3
10	10	W	SE	2600	9	5	10	1.9	17	4.3	8.8	2.2
11	15	NW	W	1100	18	4	12	1.1	7	3.6	8.3	1.2
12	20	S	N	1100	10	6	15	1.1	1	4.0	5.0	0.8
13	70	SE	NW	1900	7	7	15	1.6	12	5.8	9.8	1.4
14	38	SW	NE	2900	13	5	15	1.4	16	4.2	8.6	1.1
15	10	W	E	2300	2	6	19	2.4	20	4.4	9.3	2.4
16	2	S	E	1288	18	4	12	1	11	3.8	8.3	0.9
17	24	SE	W	2700	2	10	20	2.3	25	5.4	11.4	2.1
18	20	W	E	1500	3	11	26	2	12	6.0	11.4	2.5
19	13	E	N	2000	10	8	16	1.4	10	7.5	12.3	2.0
20	5	S	NE	1900	15	7	15	1.1	4	6.3	13.3	1.3
21	42	SE	N	1100	11	10	22	1.1	–	–	–	–
22	40	SW	E	1000	10	10	26	0.6	–	–	–	–
23	0		S	1300	12	7	12	1.6	1	5.0	8.0	1.5
24	0		W	1200	3	8	18	1.6	9	7.8	20.1	3.0
25	25	NE	NE	700	6	13	30	1.6	1	13.0	27.0	1.9
26	20	NE	NE	700	4	11	26	2.7	3	11.4	23.0	2.6
Plot average						8.5	19	1.6		7.6	13.9	2.9

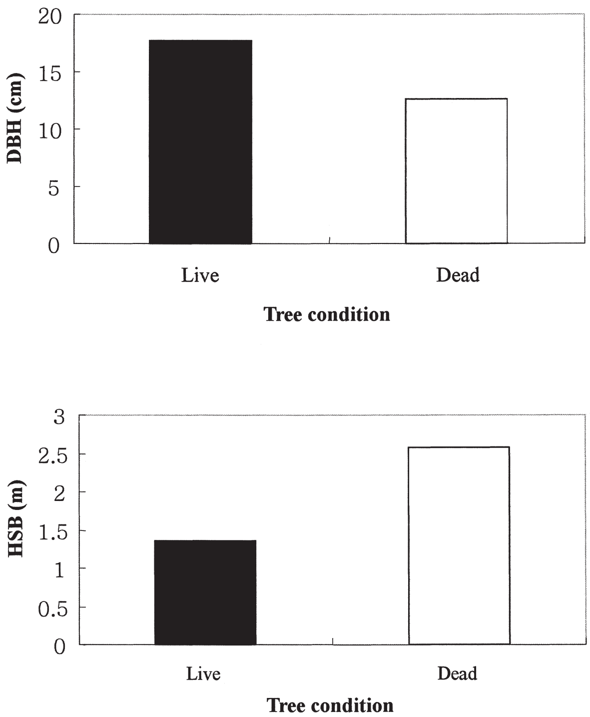

Fig. 2. Comparison of the average HSB (m) and DBH (m) observed on live and dead trees.

we conducted Mann–Whitney tests which indicated that the DBHs of the dead trees were significantly less than those of the live trees (P<0.001) and the HSBs of the dead trees were significantly greater than those of the live trees (P<0.001).

Logistic regression model

Our logistic regression model which relates the probability of Japanese red pine mortality (P) to HSB (m) and DBH (cm) is

$$P = \frac{e^{0.014-0.025\times \mathrm{DBH}+1.898\times \mathrm{HSB}}}{1+e^{0.014-0.225\times \mathrm{DBH}+1.898\times \mathrm{HSB}}} \quad [1]$$

Our model is described in detail in Table 2 which contains the estimated coefficients, standard errors and Wald statistics which pertain to each variable, and the R^2 and Chi–square statistics that can be used to assess overall model adequacy. The Nagelkerke R^2 coefficient was 0.57 and the model Chi–square statistic (236.75 with 2 degrees of freedom) was significant (P<0.001).

The probability of tree mortality decreased as DBH increased and increased as the HSB increased. Figure 3 shows how the predicted probability of mortality decreases as the DBH increases when the HSB is set to its average of 2.1 m. Figure 4 shows how the probability of mortality increases as the HSB increases when the DBH is set equal to its average of 14.7 cm.

Inter–species and inter–regional comparisons

We are not aware of any other published studies of fire induced Japanese red pine stem mortality. The bark of Japanese red pine is sometimes described as resembling that of Scots pine (*Pinus sylvestris* L.) (Farjon, 2005). We therefore compared our results with those reported by Linder *et al.* (1998) who studied post–fire mortality of Scots Pine observed after a prescribed burn carried out in a 10 ha forest reserve in northern Sweden in June of 1995. They described the fire as being of low

Table 2. Logistic regression model of the relationship between height of stem blackening (HSB), diameter at breast height (DBH) and Japanese red pine mortality

Variable	Coefficient	S.E.	Wald	Sig.	R square	Chi–square	df	P
DBH	–0.225	0.027	68.169	<.001				
HSB	1.898	0.202	87.935	<.001	0.57	236.75	2	<.001
Constant	0.004	0.334	0.002	0.966				

S.E : standard error, Wald: Wald statistic, Sig. : Statistical significance, R square : Nagelkerke R square, Chi–square : Hosmer–Lemeshow goodness–of–fit statistic, df : degrees of freedom, P : probability value.

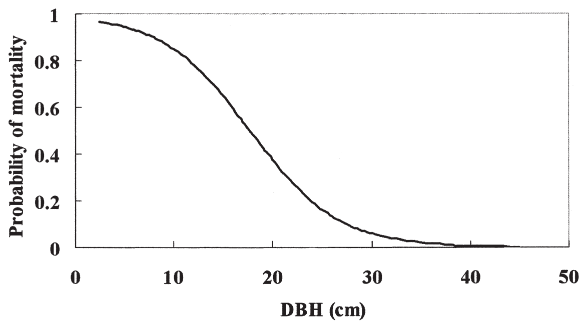

Fig. 3. Relationship between the probability of tree mortality and DBH (cm) using an average HSB of 2.1 m.

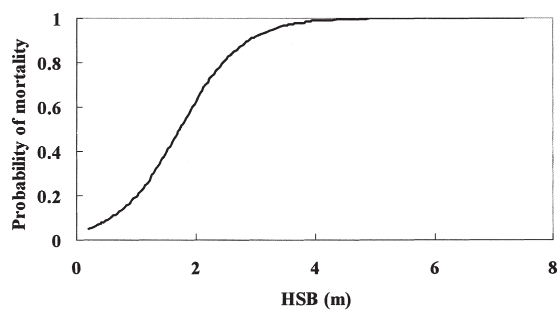

Fig. 4. Relationship between the probability of tree mortality and HSB (m) using an average DBH of 14.7 cm.

intensity, less than 700 kW/m and that "flames rarely reached above 1 m". They recorded Scots pine mortality by DBH class in October of 1995, but did not measure any tree–specific measures of fire intensity or damage other than mortality itself Their graphical results indicate they observed roughly 16% mortality for 10–20 cm DBH trees and 6% mortality for 20–30 cm DBH trees.

Although HSB tends to be less than the flame height (Cain, 1984), we compared their results with what our Japanese red pine mortality would predict for an HSB of 1 m and DBHs of 15 cm and 25 cm. Our model predicts a 18% mortality for 15 cm DBH Japanese red pine and a 2% mortality for 25 cm DBH trees. This suggests our findings are consistent with the results Linder *et al.* (1998) reported for Scots pine in Sweden.

With few exceptions (see for example, Ryan and Reinhardt, 1988 who studied post–fire mortality of seven conifer species in the Pacific Northwest of the United States) most published studies of the impact of fire on tree mortality focus on specific species and/or geographic areas. Since we found that the form of logistic regression model that Beverly and Martell (2003) used to model Eastern white pine mortality in Ontario was also well suited for modelling the impact of fire on Japanese red pine in Korea, we carried out a comparative analysis of the two models.

The average DBH and HSB observed on the 26 sample plots on the Samchuk fire were 14.7 cm and 2.1 m respectively and our model predicts a 66.6% mortality for Japanese red pine with that diameter exposed to such a fire. The Beverly and Martell (2003) model predicts a 22.6% mortality for a 14.7 cm DBH Eastern white pine with an HSB equal to 2.1 m. Assuming HSB is a reasonable surrogate measure of fire intensity, this is a very significant difference that may be attributed to inadequacies in the models, other fire attributes (e.g., flame residence time) or differences in the physical and biological properties of the two tree species.

Much of the published literature on post fire stem mortality is based on the assumption that bark insulates the cambial layer from fire induced mortality and that the insulating properties of bark vary by bark thickness within species. Comparisons are complicated by the fact that observed bark thickness is related to DBH and most researchers measure DBH rather than bark thickness. If we assume our HSB measures are comparable with those measured by Beverly and Martell (2003), the large discrepancy in predicted mortality suggests there may be significant differences in the insulating properties of Japanese red pine and Eastern white pine bark that render Eastern white pine bark a far better insulator that Japanese red pine bark.

We began by comparing the thermal conductivities of the two types of bark. Martin (1963) found that the thermal conductivity of ovendry bark increases as its density increases. If we use the specific gravity of Eastern white pine bark (0.69) reported in Hengst and Dawson (1994) and Martin's (1963) equation 4 that relates the thermal conductivity of bark to its density, we obtain a thermal conductivity of 3.3×10^{-4} cal/cm sec °C or 0.138 watts/m °K. If we use that same formula and the ovendry density of Japanese red pine bark (0.371) reported in Lee (1977), we obtain a thermal conductivity of 1.8×10^{-4} cal/cm sec °C or 0.075 watts/m °K. Given identical uniform bark, these properties would make Japanese red pine a better insulator which, taken alone, is not consistent with our results. We then turned our attention to bark thickness.

Beverly and Martell (2003) did not record the thickness of the bark on the trees they sampled but Hengst and Dawson (1998) developed empirical relationships between bark thickness and DBH for several species (including Eastern white pine) growing in plantations in Illinois. If we use the Hengst and Dawson (1998) relationship for Eastern white pine, a 14.7 cm DBH would have a predicted bark thickness of 0.8 cm. Kim *et al.* (2002) present a relationship between bark thickness and DBH for Japanese red pine. The average height of the trees sampled for this study was approximately 8 m. Assuming an 8 m Japanese red pine, the Kim *et al.* (2002) relationship predicts a bark thickness of 0.34 cm, a little less than one half the predicted thickness of bark on a similar Eastern white pine tree.

If we consider the simplest case of one dimensional heat transfer where, using Fourier's law of conduction, heat transfer would be proportional to the thermal conductivity divided by bark thickness so Japanese red pine (1.8/0.34=5.3) would be more susceptible to stem mortality than Eastern white pine (3.3/0.8=4.1).

DISCUSSION

Logistic regression model of stem mortality

Our logistic regression model has the same structure as many stem mortality models and it models the Japanese red pine mortality observed on the Samchuck fire reasonably well. As we noted above, most studies are of single species and relate stem mortality to easily measured tree attributes using regression analysis techniques. The Results can not usually be applied to other species in other areas. There is a clear need for more process based models like, for example, those described by Bova and Dickinson (2005) and Jones *et al.* (2006).

Most South Korea forest fires are salvaged after they burn and Ryan and Reinhardt (1988) note that post–fire tree mortality models can be used to help direct post–fire salvage operations to increase the likelihood that trees that are expected to experience the most mortality are salvage cut first.

Much of the Samchuck fire was salvage harvested during the second and third year after the fire occurred and that precluded the establishment of permanent sample plots that could have been used to study post fire mortality over a longer period of time. Lindenmayer *et al.* (2004) discuss the widespread practice of salvage harvesting from a global perspective and stress the need to replace hastily developed salvage operations with more carefully planned salvage harvesting. Such planning should include facilitate researchers in Korea and elsewhere working closely with the salvage harvest planners to identify and establish permanent sample plots that can be sampled over extended periods of time to track mortality over extended periods of time.

Inter–species and inter–regional comparisons

The thermal conductivity and bark thickness of Japanese red pine do not explain the predicted three–fold difference in mortality of trees with a DBH of 14.7 cm subjected to an HSB of 2.1 m when compare with white pine. One tree attribute that may make Japanese red pine more susceptible to stem mortality than Eastern white pine is bark fissures. Fahnestock and Hare (1964) reported that a small sample (4 observations) of maximum temperatures recorded in the fissures on the leeward side of longleaf pine trees were less than the maximum temperatures recorded on the bark plates of those same trees. They characterized their bark fissures as "shallow and frequently not well defined". In their discussion of bark thickness, Dickinson and Johnson (2001) cite Fahnestock and Hare (1964) and suggest that lower temperatures in bark fissures may counteract the effects of the thinner bark there but they suggest using two or three dimensional numerical heat transfer models to explore the effects of bark fissuring. Jones *et al*. (2006) drew upon Kayll's (1963) conclusion that was reasonable to ignore heat transfer through fissures to justify their assumption that it was not necessary for them to address fissure properties of bark in their recent model of thermally induced cambial tissue necrosis in tree stems. However, Japanese red pine is considered to have a very rough bark. The photographs in Fig. 5 are of a Japanese red pine tree with a DBH of 17 cm which was cut in the Kangwon National University Forest in April of 2006. The bark thickness ranged from as little ad 0.2 cm in the fissures to as large as 1.8 cm on the bark plates. Such variability suggests that heat transfer through the wide bark fissures evident in Figure 5 may be more important for Japanese red pine than it is for many other species.

Bark is well known to have a significant impact on tree mortality and its thickness and thermal conductivity are most often mentioned in the literature. Since there are well documented species–specific relationships between bark thickness and DBH (see for example, the studies summarized in Table 3 of Ryan and Reinhardt, 1998) researchers often use the easily measured DBH rather than bark thickness to characterize a tree's bark. However, as Ryan and Reinhardt (1998) point out "bark thickness to diameter ratios vary somewhat according to site and ecotype" which may dictate the need to measure bark thickness and may make it difficult to apply models developed using some sites to other sites.

CONCLUSION

We were able to relate Japanese red pine fire induced mortality to easily measured fire and tree attributes. The model could be used to help plan prescribed burns and to guide post–fire salvage logging operations that are common in Korea.

Fig. 5. Photographs of the stem and a cross section of the stem of a Japanese red pine which contains wide deep bark fissures that may influence stem mortality.

Japanese red pine has bark that resembles the bark of Scots pine and we found our results are similar to those reported for fire induced Scots pine mortality in Sweden. However, our comparison with a model of fire induced mortality of Eastern white pine in Canada revealed a need to look beyond DBH and study the impact of other bark attributes such as bark fissures on fire induced mortality and eventually develop more explicitly process–based tree mortality models.

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