Jour. Korean For. Soc. Vol. 99, No. 2, pp. 163~171 (2010)

JOURNAL OF KOREAN
FOREST SOCIETY

Meteorological Determinants of Forest Fire Occurrence in the Fall, South Korea

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Abstract : Forest fires have potentials to change the structure and function of forest ecosystems and significantly influence on atmosphere and biogeochemical cycles. Forest fire also affects the quality of public benefits such as carbon sequestration, soil fertility, grazing value, biodiversity, or tourism. The prediction of fire occurrence and its spread is critical to the forest managers for allocating resources and developing the forest fire danger rating system. Most of fires were human-caused fires in Korea, but meteorological factors are also big contributors to fire behaviors and its spread. Thus, meteorological factors as well as social factors were considered in the fire danger rating systems. A total of 298 forest fires occurred during the fall season from 2002 to 2006 in South Korea were considered for developing a logistic model of forest fire occurrence. The results of statistical analysis show that only effective humidity and temperature significantly affected the logistic models ($p<0.05$). The results of ROC curve analysis showed that the probability of randomly selected fires ranges from 0.739 to 0.876, which represent a relatively high accuracy of the developed model. These findings would be necessary for the policy makers in South Korea for the prevention of forest fires.

Key words : *forest fire danger rating, logistic regression, temperature, effective humidity*

Introduction

Fire ignition, spread, and impacts were influenced by the interactions between weather conditions, vegetation structure and land use, on various temporal or spatial scales (Flannigan, 2006; Martín *et al.,* 1997). It was proved that forest fires are potential to change the structure and functioning of ecosystems posing a significant impact on atmosphere and biogeochemical cycles. It also modifies the provision of ecosystem services notably carbon sequestration, soil fertility, grazing value, biodiversity and tourism (Schimel and Baker, 2002). A report drawn from the satellite data showed that 350 million hectares of land area was affected by vegetation fires worldwide in the year 2000, much of which was forest and woodland (FAO, 2007). It has also been reported that in the Northeast Asia including the South Korea, about 1 million hectare of forests in average were burned each year between 1990 and 2004. A huge property loss of US $83 million was recorded in April 2000, with severe impacts on the forests as well. It is also evident that the number of catastrophic fires burning across large areas is being increased. Fire risk could be influenced climate change, ignition sources, length of the fire season, vegetation structure, land-use changes and institutional constraints for sustainable forest or fire management (FAO, 2007; Flannigan *et al*., 2000). Understanding of forest fire ignition and its spread is critical to prevent catastrophic forest fires and provide the forest fire risk alert at a specific region and a season.

Prediction of fire occurrence and its spread in a certain season for a given area is necessary for the forest managers to help them to allocate resources and to develop the forest fire danger rating system (Andrews and Queen, 2001). Based on the fire danger risk and the fire environment (e.g. meteorological factors), it is able to systematically evaluate and integrate the factors easing the forest fire ignition and its spread (Countryman, 1966). In South Korea, forest fires are not the natural events, but rather anthropogenic accidents depending on human activities, such as carelessness, weed burning, fireworks, and other activities inside the forests (Lee *et al*., 2006). FAO (2007) reports that 79% of the forest

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fires occurred in South Korea were overwhelmingly originated from human activities. In South Korea, coniferous trees covers about 42% of forest lands and *Pinus densiflora* covers about 58% of the coniferous forest. Coniferous species in South Korea are considered to be vulnerable to fire. In fall, the seasonal wind blowing from the continent creates dry seasons in Korea and poses to the fire hazards. Even though forest fires in South Korea were caused by human activities, fire behaviors and its spread were mainly influenced by meteorological factors, such as temperature, effective humidity, precipitation (Flannigan, 2006; Chandler *et al.*, 1983).

Lee *et al.* (2004) developed a probability model of forest fire occurrence for the spring season, a severe fire season in South Korea, by using the meteorological data. Lee *et al.* (2005) also developed forest fire occurrence danger index using fuel and topographical conditions of ignition points in South Korea. Lee *et al.* (2006) analyzed the temporal and spatial characteristics of forest fires in South Korea between 1970 and 2003. Shin and Lee (2004) described the restoration strategies for forest ecosystems degraded by forest fire in Gangwon province in South Korea. From 2003, Korea Forest Research Institute has predicted national fire danger rating by using probability model of forest fire occurrence for the severe season (from January to May). However, there is a problem to use the model for the fall season because weather conditions are quietly different between the spring and the fall. There was no probability model available to predict forest fire occurrence and its spread for the fall in South Korea. This study aimed at developing a probability model to predict forest fire occurrence for the fall in eight different provinces of the South Korea based on the meteorological data of forest fires occurred from 2002 to 2006.

Materials and Methods

1. General forest fire environments in South Korea

South Korea is a temperate country located at the heart of the North Western Pacific region. The Korean peninsula encompasses 221,000 km^2, 45% of which (99,600 km^2) makes up the South Korea ranging between 125° 04' and 131° 52' E longitude and between 36° 06' and 38°27' N latitude. South Korea has a temperate climate with four distinct seasons. It is dry and cold during the winter due to the northwesterly wind sweeping down from Siberia. South Korea has hotter summers and colder winters compared to the other countries located in the same latitude zone of the continent. The most severe fire season is spring that has a dry and warm weather. Annual average temperature is 12-14°C in the central region and 3-10°C in the northern region. Annual mean precipitation ranges from 600 mm to 1,600 mm with seasonal variation (KFS, 2006). In 2005 South Korea has 6.39 million ha of forests covering about 64.2% of the total land area, of which nearly 42.3% (2.70 million ha) is coniferous forest. The broadleaved and mixed forests cover 25.9% (1.66 million ha) and 29.3% (1.87 million ha), respectively, with the remaining 2.5% (0.16 million ha) being classified as miscellaneous types. Nearly 60% of forests are young stands less than 40 years (KFS, 2006). With the increase in the forest age, woody fuel, ground litter and forest visitors, the forest fire risk has been significantly increasing. Therefore, forest managers are in a high pressure to prevent and control forest fires. In April 2000, a catastrophic forest fire encompassing 23,794 ha occurred in mountainous areas near the East Coast Gangwon province. This fire was recorded as the most disastrous forest fire since 1945, causing massive property damage. On average, from 1999 to 2008, 497 fires burned 3,637 ha of forest lands each year in South Korea. All fires were occurred due to human activities, especially agricultural burning in rural areas adjacent to forests.

2. Method

To develop a probability model of forest fire occurrence, a total of 298 forest fires occurred during the fall (September to December) from 2002 to 2006 were selected. Meteorological data such as temperature, relative humidity, wind speed at the ignition time, and daily precipitation of the nearest date before the ignition, were collected from the Korea Meteorological Administration (KMA, 2007). The effective humidity was calculated by weighing the relative humidity of a given ignition day and the previous four days using the following equation (1):

$$H_e = \frac{H + r(H_1) + r^2(H_2) + r^3(H_3) + r^4(H_4)}{1 + r + r^2 + r^3 + r^4} \tag{1}$$

Here, H_e is the effective humidity, H_0 is the relative humidity of the given ignition day, H_n is the relative humidity of n previous days, and r is the coefficient of effective humidity. In this study, the value of r was fixed at 0.7.

The forest fire occurrence observation encompasses the eight provinces of the Republic of Korea, i.e., Chungbuk, Chungnam, Chunbuk, Chunnam, Gangwon, Gyunggi, Gyungbuk and Gyungnam. The ignition locations of fires were demarcated by the nearest weather stations. A total of 55 weather stations were encountered for this study. With the specific day of ignition and the corresponding weather stations, the data were collected. This study includes the forest fires occurred from September, 2002 to December, 2006.

3. Probabilistic risk assessment

To understand meteorological characteristics in the study regions it needs to make an analysis of statistical methods like canonical correlations analysis (CCA). CCA is used when multivariate measurements are portioned into two sets. CCA finds linear combinations in the two sets that have the largest possible correlation (Ramsey and Schafer, 1997). That is canonical discriminant analysis is a dimension-reduction technique related to principal component analysis and canonical correlation. Given a nominal classification variable and several interval variables, canonical discriminant analysis derives canonical variables (linear combinations of the interval variables) that summarize between-class variation in much the same way that principal components summarize total variation.

Dayananda (1977), Poulin-Costello (1993), Mandallaz and Ye (1997) employed Poisson model to explain the number of forest fires. Preisler *et al.* (2004), Chou *et al.* (1993) and Martell *et al.* (1987) used the logistic model to assess the fire occurrence probability. Also, Loftsgaarden and Andrews (1992) used the logistic regression to develop the forest fire danger rating system, and Garcia *et al.* (1995) used it to predict the number of firedays. In addition, Vasconcelos *et al.* (2001) used the logistic regression for prediction of fire ignition location. Martell (1999) used Markov chain models for estimating occurrence probability of relationship between wildfire and weather variables. Wildfire incidences were related with temperature, precipitation, fuel moisture and fire history for Los Angeles County (Peng and Schoenberg, 2001; Schoenberg *et al*., 2000).

Probabilistic risk assessment was used to estimate the probabilities of hazardous events which took place within a specified time period and in a specified context (Brillinger *et al*., 2003). It proceeded by reducing a complex situation to its simpler components, followed by the fitting and validation of stochastic models associated with the components. The probability framework is necessary to assess the utility of explanatory variables, such as weather condition at the ignition time. A non-parametric logistic regression with stratified data for each province was employed to model the probability of fire occurrence. Brillinger *et al*. (2003) state that fire occurrence depends on local conditions such as location, elevation, wind speed, precipitation, temperature, humidity, topography, litter type, level of suppression and so on. The explanatory variables in this study are temperature (°C), effective humidity (%) (calculated from the relative humidity), wind speed (m/sec) at the ignition time; and daily precipitation (mm) at the nearest date of the ignition day and the duration (day) between rainfall and ignition day. These factors were considered as explanatory variables in our model with an assumption that a fire spread out after ignition when the variables at a given location exceed a threshold level.

4. Logistic regression

In this study, logistic regression was used to predict fire occurrence probability with meteorological factors and fire history. The logistic function determining the fire occurrence probability is the '*Logit*' function. In fact the logistic model determined the actual percentages of an event as a function of a number of explanatory variables with a constant and coefficients. *Logit(P)* is the log (to base *e*) of the odds or likelihood ratio that the dependent variable is 1. It can be defined as:

$$Logit(p) = \log(p/(1-p)) \tag{2}$$

Here, p has a value ranging from 0 to 1, while *Logit(P)* has a value from negative infinity to positive infinity.

The logistic regression equation was resulted as below:

$$\ln(p/1-p) = \beta_0+\beta_1 X_1+\ldots+\beta_1 X_1 \tag{3}$$

To make a more general equation, we reversed the Logit equation as followings:

$$p = \frac{\exp(\beta_0+\beta_1 X_1+\ldots+\beta_j X_j)}{1+\exp(\beta_0+\beta_1 X_1+\ldots+\beta_j X_j)} \tag{4}$$

Here, p is the probability of the fire occurrence, exp is the exponential function, $X_{1\cdots j}$ are the explanatory variables, β_0 is the intercept, and $\beta_{1\cdots j}$ is the coefficients for explanatory variables.

Receiver operating characteristic (ROC) curve was used for verifying the probability of the fire occurrence in the fall. The ROC curve is a plot of test sensitivity as the y coordinate versus its 1-specificity or false positive rate as the × coordinate. It is an effective method of evaluating the performance of diagnostic tests.

5. Fire danger rating

Chandler *et al.* (1983) defined the forest fire danger as an index based on fuel types, topography and weather conditions which affect the fire ignition, its spread and behaviors. The National Fire Danger Rating System (NFDRS) of the United State was developed the basis on the research of mathematics and physics of fuel moisture and heat exchange (Rothermel, 1972). The U.S. and Canadian models were also developed from the statistical analysis of large field data (Van Wagner, 1974; Lee *et al.,* 2002). The statistical models applied in this study was also used optimistically in the NFDRS. The literature reviews of the forest fire danger rating showed that Canada and U.S. NFDRS can be a good example for developing NFDRS of South Korea (Wybo *et al.,* 1995). In a ROC curve the true positive rate (Sensitivity) is plotted in function of the false positive rate (1-Specificity) for different cut-off points. Each point on the ROC plot represents a sensitivity/specificity pair corresponding to a particular decision threshold. A test with perfect discrimination (no overlap in the two distributions) has a ROC plot that passes through the upper left corner (100% sensitivity, 100% specificity). Therefore the closer the ROC plot is to the upper left corner, the higher the overall accuracy of the test (Zweig and Campbell, 1993).

Results and Discussion

Maximum number of fires in the fall from 2002 to 2006 was found in Gyungnam (78, 26.2%) and the min-

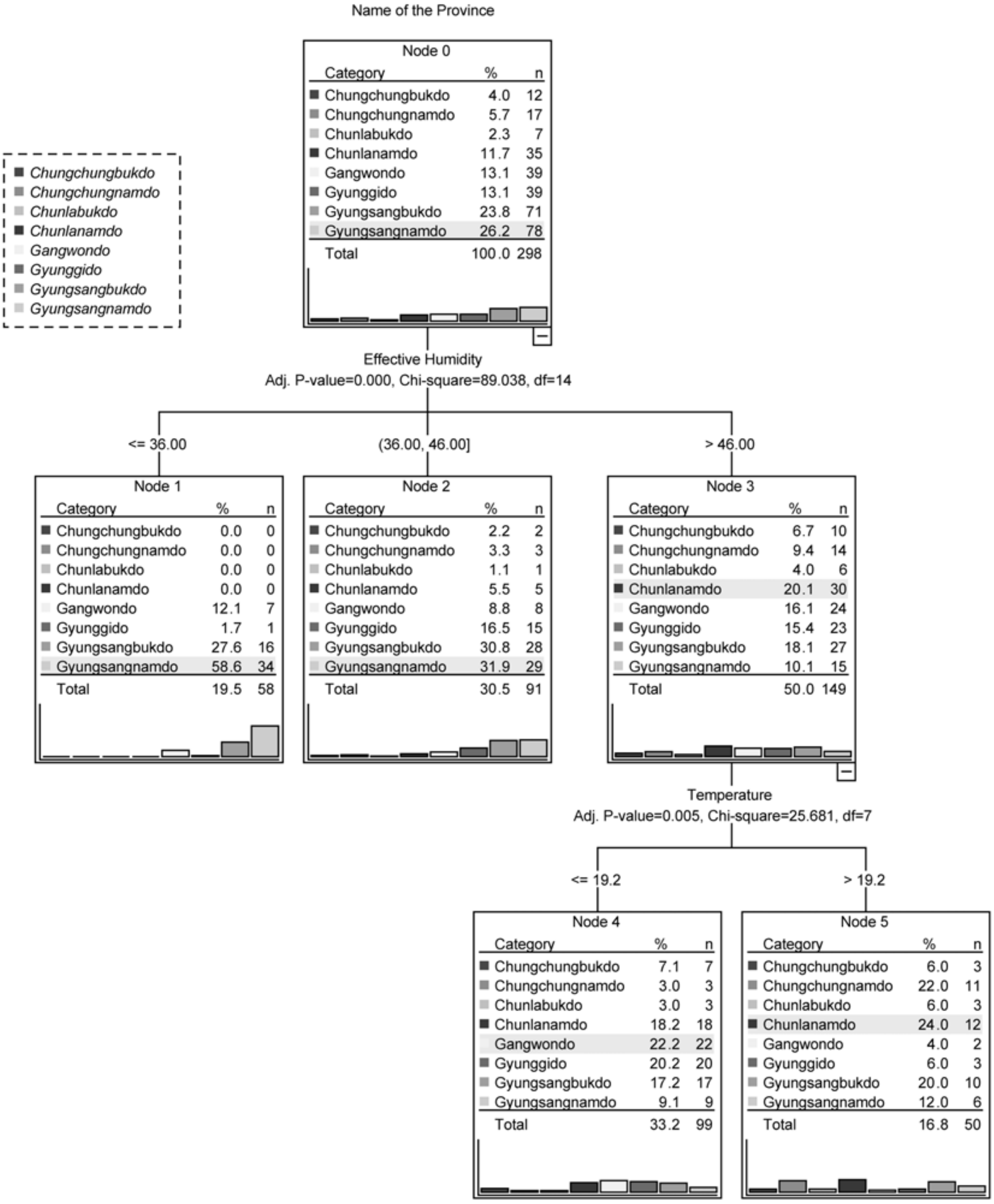
Table 1. Fire occurrence and the corresponding meteorological factors in the eight provinces.

Province		Temperature (°C)	Effective humidity (%)	Wind speed (m/sec)	Duration between rainfall and ignition day (day)	Daily precipitation (mm)
Chungbuk	n	12	12	12	12	12
	Mean	11.9	53	2.9	8.00	3.4
	Std. Error of Mean	2.45	1.61	.418	1.91	.76
	Minimum	-2.5	42.00	.6	0	.2
	Maximum	24.8	61.00	5.4	17	9.5
Chungnam	n	17	17	17	17	17
	Mean	19.4	51	2.2	9.00	1.4
	Std. Error of Mean	1.92	1.15	.23	1.51	.44
	Minimum	.2	40.00	.4	0	.5
	Maximum	27.2	61.00	4.1	19	6.0
Chunbuk	n	7	7	7	7	7
	Mean	12.5	53	2.5	11.71	3.5
	Std. Error of Mean	4.49	2.78	.29	3.02	1.88
	Minimum	.3	43.00	1.2	0	.2
	Maximum	27.2	63.00	3.5	25	13.5
Chunnam	n	35	35	35	35	35
	Mean	16.0	54	3.7	6.60	4.9
	Std. Error of Mean	1.20	1.35	.47	.90	1.81
	Minimum	1.2	39.00	.0	0	.1
	Maximum	28.6	75.00	10.2	27	56.0
Gangwon	n	39	39	39	39	39
	Mean	10.6	49	3.00	7.36	5.6
	Std. Error of Mean	1.13	1.66	.35	1.15	1.33
	Minimum	-4.4	23.00	.6	0	.1
	Maximum	22.3	69.00	10.6	24	35.5
Gyunggi	n	39	39	39	39	39
	Mean	10.1	49	2.37	7.64	5.2
	Std. Error of Mean	1.16	1.08	.22	1.11	1.29
	Minimum	-5.4	32.00	.0	0	.1
	Maximum	26.1	66.00	5.8	27	32.5
Gyungbuk	n	71	71	71	71	71
	Mean	9.0	45	2.9	9.27	4.3
	Std. Error of Mean	1.12	1.25	.21	.90	.81
	Minimum	-11.6	22.00	.0	0	.1
	Maximum	26.6	63.00	7.7	31	36.5
Gyungnam	n	78	78	78	78	78
	Mean	8.9	39	2.96	10.67	4.5
	Std. Error of Mean	.92	1.12	.18	.76	.73
	Minimum	-8.6	18.00	.4	0	.1
	Maximum	28.7	61.00	6.3	26	30.0

Table 2. Annual forest fire occurrence from 2002 to 2006 in the eight provinces.

Province		Year					Total
		2002	2003	2004	2005	2006	
Chungbuk	n	1 (2.4)*	1 (2.3)	1 (1.5)	3 (3.6)	6 (9.4)	12 (4.0)
Chungnam	n	0	2 (4.7)	4 (6.1)	2 (2.4)	9 (14.1)	17 (5.7)
Chunbuk	n	2 (4.8)	0	2 (3.0)	1 (1.2)	2 (3.1)	7 (2.3)
Chunnam	n	4 (9.5)	1 (2.3)	11 (16.7)	8 (9.6)	11 (17.2)	35 (11.7)
Gangwon	n	7 (16.7)	1 (2.3)	11 (16.7)	9 (10.8)	11 (17.2)	39 (13.1)
Gyunggi	n	6 (14.3)	6 (14.0)	14 (21.2)	5 (6.0)	8 (12.5)	39 (13.1)
Gyungbuk	n	8 (19.0)	10 (23.3)	12 (18.2)	28 (33.7)	13 (20.3)	71 (23.8)
Gyungnam	n	14 (33.3)	22 (51.2)	11 (16.7)	27 (32.5)	4 (6.3)	78 (26.2)
Total	n	42 (100)	43 (100)	66 (100)	83 (100)	64 (100)	298 (100)

*Number in the parenthesis means the percentage value



Node 0

Category	%	n
Chungchungbukdo	4.0	12
Chungchungnamdo	5.7	17
Chunlabukdo	2.3	7
Chunlanamdo	11.7	35
Gangwondo	13.1	39
Gyunggido	13.1	39
Gyungsangbukdo	23.8	71
Gyungsangnamdo	26.2	78
Total	100.0	298

Node 1

Category	%	n
Chungchungbukdo	0.0	0
Chungchungnamdo	0.0	0
Chunlabukdo	0.0	0
Chunlanamdo	0.0	0
Gangwondo	12.1	7
Gyunggido	1.7	1
Gyungsangbukdo	27.6	16
Gyungsangnamdo	58.6	34
Total	19.5	58

Node 2

Category	%	n
Chungchungbukdo	2.2	2
Chungchungnamdo	3.3	3
Chunlabukdo	1.1	1
Chunlanamdo	5.5	5
Gangwondo	8.8	8
Gyunggido	16.5	15
Gyungsangbukdo	30.8	28
Gyungsangnamdo	31.9	29
Total	30.5	91

Node 3

Category	%	n
Chungchungbukdo	6.7	10
Chungchungnamdo	9.4	14
Chunlabukdo	4.0	6
Chunlanamdo	20.1	30
Gangwondo	16.1	24
Gyunggido	15.4	23
Gyungsangbukdo	18.1	27
Gyungsangnamdo	10.1	15
Total	50.0	149

Node 4

Category	%	n
Chungchungbukdo	7.1	7
Chungchungnamdo	3.0	3
Chunlabukdo	3.0	3
Chunlanamdo	18.2	18
Gangwondo	22.2	22
Gyunggido	20.2	20
Gyungsangbukdo	17.2	17
Gyungsangnamdo	9.1	9
Total	33.2	99

Node 5

Category	%	n
Chungchungbukdo	6.0	3
Chungchungnamdo	22.0	11
Chunlabukdo	6.0	3
Chunlanamdo	24.0	12
Gangwondo	4.0	2
Gyunggido	6.0	3
Gyungsangbukdo	20.0	10
Gyungsangnamdo	12.0	6
Total	16.8	50

Figure 1. Classification tree for discriminating the regions for predicting fire occurrence in South Korea.

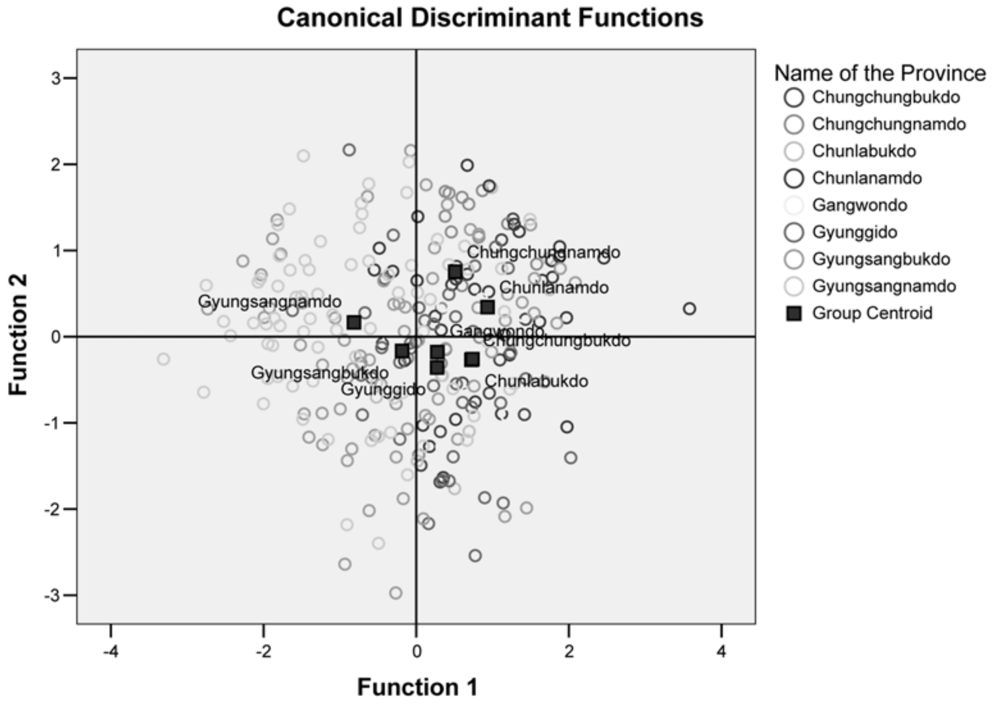


Figure 2. Canonical discriminant functions showing the eight provinces for predicting fire occurrence in South Korea.

imum was found in Chungbuk (12, 4%) (Table 1 and Table 2). Mean temperature, effective humidity, wind speed, duration between rainfall and ignition day and daily precipitation at the nearest date of the ignition day were 8.9ºC, 39%, 3.0 m/sec, 10.67 days and 4.5 mm in Gyungnam. The same meteorological data for Chungbuk were 11.9ºC, 53%, 2.9 m/sec, 8 days and 3.4 mm, respectively. Maximum number of fires was observed in 2005 (83) and the minimum was recorded in 2002 (42) (Table 2).

1. Meteorological characteristics in the study regions

The results showed that the eight provinces were significantly discriminated by the effective humidity and temperature ($p<0.05$ and $p<0.01$, x^2=89.038 and 25.681) (Figure 1). Effective humidity was appeared as the most effective weather factors. Discriminating the eight regions to three levels, i.e., 36%, 36-46% and >46%. Temperature was another important factor discriminating the regions to two levels, i.e., 19.2ºC and >19.2ºC. The centroids of the eight regions depicted in the Figure 2 also indicate that the eight regions were discriminated by the two weather factors.

2. Probability model for forest fire occurrence

For the eight different regions, forest fire probability was predicted with the given meteorological factors. Effective humidity and temperature were the significant factors in the logistic regression as well ($p<0.05$ and $p<0.01$). The coefficients and constants resulted from the logistic regression are shown in the table 3. The probability models of equation (4) for the eight different regions are shown in the table 4.

Wind speed was reported as an important factor for predicting fire risk and development (Martín *et al.,* 1997). Preisler *et al*. (2004) also reported a similar result in

Table 3. Parameter estimates for the probability of forest fire occurrence in the eight provinces.

	Name of the region/province							
	Chungbuk	Chungnam	Chunbuk	Chunnam	Gangwon	Gyunggi	Gyungbuk	Gyungnam
Effective humidity	0.720**	0.636**	0.721**	0.703**	0.665**	0.678**	0.615**	0.526**
Temperature	-0.210**	-0.054**	-0.202**	-0.140**	-0.201**	-0.214**	-0.197**	-0.152**
Constant	-20.971	-18.704	-21.708	-20.003	-17.158	-17.613	-14.239	-10.869
Nagelkerke R^2	0.749	0.35	0.721	0.43	0.28	0.28	0.93	0.26
Hosmer and Limeshow goodness-of-fit statistics	0.715	0.993	0.823	0.595	0.651	0.489	0.466	.337
Predicted accuracy (%)	83.3	58.8	57.1	68.6	59	71.8	64.8	60.3

Table 4. Forest fire occurrence probability model resulted from the logistic regression analysis.

Regions	Probability model
Chungbuk	$[1+\{\exp(-20.971+(0.720\times EF^{*})-(0.210\times Tmean^{**}))\}]^{-1}$
Chungnam	$[1+\{\exp(-18.704+(0.636\times EF)-(0.054\times Tmean))\}]^{-1}$
Chunbuk	$[1+\{\exp(-21.708+(0.721\times EF)-(0.202\times Tmean))\}]^{-1}$
Chunnam	$[1+\{\exp(-20.003+(0.703\times EF)-(0.140\times Tmean))\}]^{-1}$
Gangwon	$[1+\{\exp(-17.158+(0.665\times EF)-(0.201\times Tmean))\}]^{-1}$
Gyunggi	$[1+\{\exp(-17.613+(0.678\times EF)-(0.214\times Tmean))\}]^{-1}$
Gyungbuk	$[1+\{\exp(-14.239-(0.197\times EF)+(0.615\times Tmean))\}]^{-1}$
Gyungnam	$[1+\{\exp(-10.869+(0.526\times EF)-(0.152\times Tmean))\}]^{-1}$

*EF : effective humidity
**Tmean : mean temperature.

their study. However, wind speed was not an effective weather factor to the fire occurrence probability ($p>0.05$) in this study. The distance between the weather station and the fire initiation points could be a confounding factor to examine the effects of wind speed on the model. The duration between ignition day and the latest rainfall, daily precipitation at the latest day, were not significant factors ($p>0.05$) on the model either. The distance between the ignition point and the reference weather station could be a confounding factor in this case as well.

In the probability models of forest fire occurrence in spring, a severe fire season in South Korea, effective humidity, wind speed and temperature were the important determinants (Lee *et al.,* 2004). However, wind speed was not an important determinant in the probability model of the fall season. It can be due to the seasonal variation of wind speed. The constants for the logistic functions used in the models of Lee *et al.* (2004) ranged from 2.216 to 7.405 for all the provinces, while in this study they ranged from -20.971 to -10.869 for all the provinces. It also can be explained by the seasonal variation of temperature and relative humidity. The ROC curve and area under the curve reveal that using the models developed in this study provided better prediction of fire occurrence ($p<0.05$). The area under the curve ranges from 0.739 to 0.876 (Figure 3). The probability model for Gangwon showed the least adequate probability (0.739) whereas that for Gyunggi showed the most adequate probability (0.876).

Conclusions and Recommendations

In this study, we found that effective humidity and temperature were major meteorological factors determining the probability of forest fires in fall for all the eight regions in South Korea. The ROC curve estimation for the prediction model also showed the adequacy of the prediction in the eight regions. For the better prediction of forest fire occurrence, it is necessary to consider some more variables along with the fire weather. Fire management information systems for the non-sever fire season in South Korea could be beneficial for fire management during the season. Recently Korea Forest Research Institute developed databases for fire weather and fire occurrence. The probability models of the fall for eight provinces can be useful to the policy makers of forest fire prevention in Korea. The fire data warehouse could facilitate the collaborative research or management among the wide range of research field including forest policy, forest management, forest fire science, forest health, forest inventory, global change, forest economics and remote sensing (Lee *et al.,* 2002).

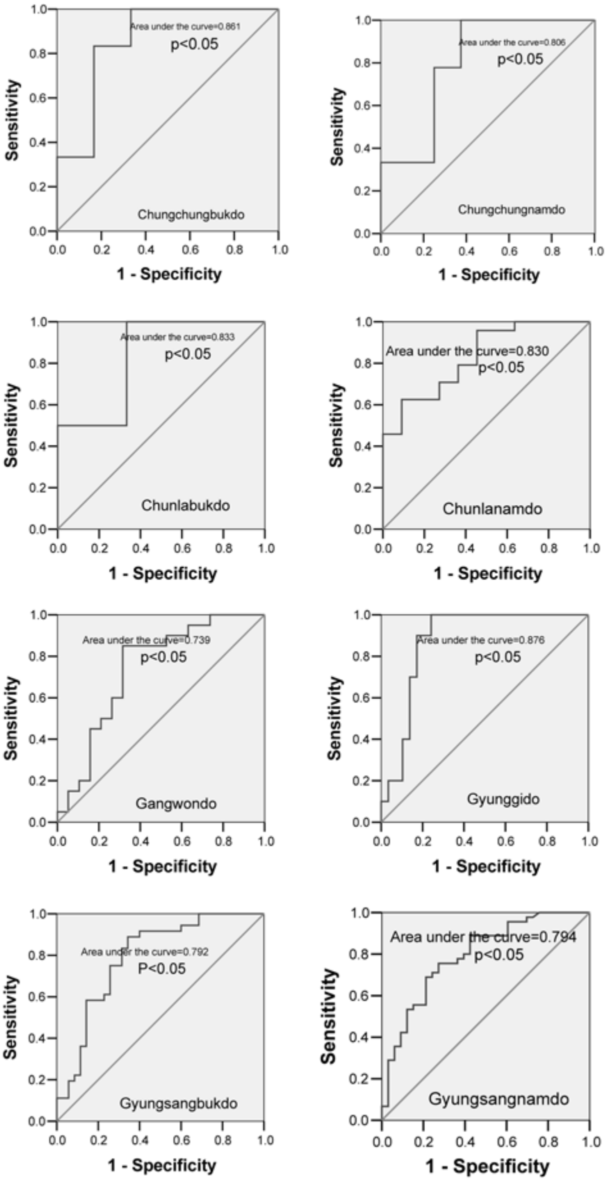


Figure 3. ROC curve estimation for the eight provinces for the probability of forest fire occurrence in the fall season in South Korea.

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(Received September 30, 2009; Accepted January 25, 2010)