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The Effects of Climate on Occurrence of Spring Forest Fires in the Mountainous Region of Gangwon-do*

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Abstract : This study estimated the fire climate variables strongly associated with occurrence of forest fires in the mountainous region of Gangwon-do by analyzing the correlation between the number of forest fires in spring and precipitation, number of days with precipitation, relative humidity, and snowfall before fire season. Two distinct fire regimes are identified in the diurnal variation of fire occurrence: night – early morning and late morning – late afternoon. These two regimes are separated by a increase of fire occurrence in the morning and a decrease of fire occurrence at night. The number of spring forest fires in the mountainous region of Gangwon-do had negative relationship with precipitation, number of precipitation days, relative humidity, and snowfall during winter to early spring (December-January-February-March). In particular, while the number of days with precipitation $\leqq$ 0.2 mm during DJFM showed no significant relationship, the number of days with precipitation $\geqq$ 0.3 mm was significantly correlated with the forest fire occurrences of spring. Also, The annual number of forest fires was significantly correlated with spring precipitation for a time-lag of 2 years, suggesting that high precipitation during spring may increase fuel loads that burn 2 years later. The minimum relative humidity of fire occurrence day has a significantly negative relationship with the burn velocity of forest fire, and the large fires more than 30 ha occurred in the day with minimum relative humidity below 20%.

Key Words : Climate, Spring forest fires, Precipitation, Number of days with precipitation, Relative humidity, Snowfall

I. Introduction

One of the major environmental concerns in mountainous region is the occurrence of devastating forest fires. Fire activity is strongly influenced by four factors - climate/weather, fuels, ignition agents, and human activities (Swetnam, 1993). Among the these factors that determine forest fire behavior, Goens (1990) argued that weather is the most important variable in the real-time fire-control situation.

Fires has been an important component of natural and is also recognized as a significant disturbance factor in several ecosystems (Roberts, 2000). Fire may profoundly alter the structure of the landscape and can affect ecological processes. Further, forest fires are an important source of aerosols. Outdoor fires can emit substantial amounts of particulate matter (PM) and other pollutants into the atmosphere. These emissions may significantly impact air quality on both local and regional scales (Vander Werf *et al.*, 2003). Also, fires in forest pose a risk to people and cause substantial financial losses. The fires of 6-15th April 2000 in the eastern coastal area burned 234 hundred hectares and the damage of forest was

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estimated about 606 hundred million won (Lim, 2000).

Many studies that examined the relationship between fire and climate/weather variables were primarily devoted to the forest fire in large wildland areas, such as the U.S. West region, the Northwest Territories of Canada, and the large landmass of Australia. Included in these studies were the examination of the synoptic conditions associated with wildland fires (Brotak and Reifsnyder, 1977; Flannigan and Harrington, 1987), the relationship of jet streams with forest fires (Schaefer, 1957), and the role of meteorological variables in a specific forest fire (Kondo and Kuwagata, 1992). Martin (1982) showed that the highest fire frequency occurs with dry conditions that favor wildland fuel (i.e., buring sustances in the forest fires, including living and dead fuels such as duff, roots, peat, rotten wood, bark, tree leaves, branches, grasses, forbs, shrubs, etc.) accumulation. Using meteorological variables as predictors in a statistical study, Flannigan and Harrington (1988) concluded that long sequential days without rain (<1.5 mm) combined with low relative humidities (<60%) have the highest correlation with wildfires in Canada. Close relationships between the atmospheric conditions and fires were observed in these studies.

Also, recent research applying predictions of general circulation models (GCMs) has consistently found that predicted climate change will lead to increases in the frequency of weather conditions associated with high wildfire hazard. In these analyses a double-CO2 climate led to changes in weather-related indices of potential fire intensity and rate of speed (Stocks *et al*., 1998; Williams *et al*., 2001; Wotton *et al*., 2003; Fried *et al*., 2004), increases in fire ignitions (Goldhammer and Price, 1998), and lengthening of the fire season (Wotton and Flannigan, 1993).

Previous studies on mountain regions over Korea have focused on the growth characteristics of forests and the impacts of climate change (Lee and Kim, 2008; Lee and Lee, 2008; Chun *et al*., 2009). However, the analyses of the effects of climate on forest fire risk in Korea was very rare. Won *et al*. (2006) examined forest fire occurrence hazards according to the change of temperature and humidity at interval of ten days. In this study, forest fire hazards occurred in the spring season form the end of March to the middle of April, and the estimation of forest fire occurrence hazards during early April was very high at Gyeongbuk Interior, Chungcheong Interior and part of Gangwon.

Little research attention has been paid to the temporal variation of fire occurrence and its relationship with the periodic variation of climatic conditions, especially using the fire history of a region and instrumentally observed climatic data. The objectives of this study are to identify the fire climate variables strongly associated with forest fire occurrence in the mountainous region of Gangwon-do.

II. Data and Methods

The study area corresponds to 36 eup-myeon-dong boundaries of the mountainous region in Gangwon-do (Fig. 1). The each area over than 600 meters in altitude in 36 eup-myeon-dong account for more 50 percent of each total areas. The eup, myeon, and dong except for ri are the smallest administrative district in Korea. As the central mountainous region over Korea classified by 600 meter boundary in Lee *et al*. (2005), 600 meter boundary was used to define

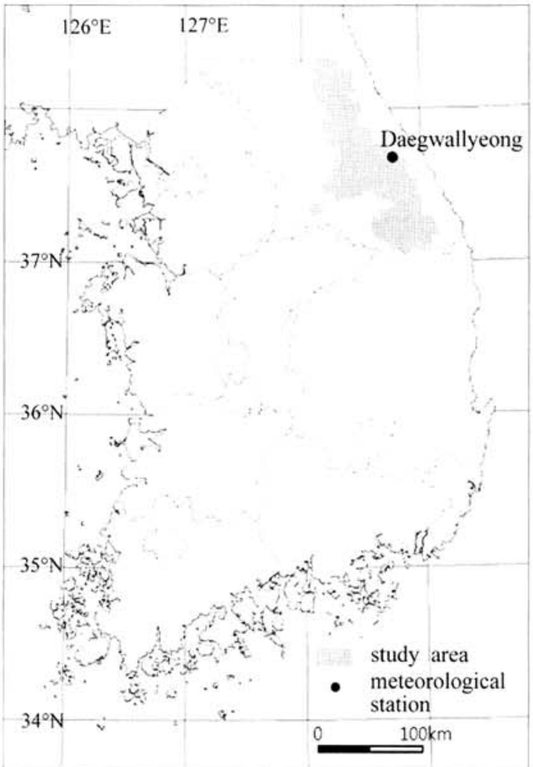

Fig. 1. The study area and location of the meteorological station

study area. The present study is based largely on the analysis of the meteorological record for the Daegwallyeong meteorological observatory. Daegwallyeong has the longest and most continuous meteorological record of the area, and is located in higher than 600 meters in altitude (772.4 meters).

Fire occurrence data was obtained from Annual Report of Forest Fire published in the Korea Forest Service for 1989-2008, and include information such as ignition date, control date, address, cause, area burned. Continuous statistics for forest fires in Korea are available since 1989. From theses data, the annual and monthly number of fires and the annual area burned were computed. The fire characteristics for the mountainous region of Gangwon-do were examined with the time series of fire occurrence and burned area. Forest fires occur throughout the year, but in the spring months they are much more frequent. In this paper the main fire season is spring (March to May). In the paper the term 'spring' and 'fire season' are used as synonyms.

Climate data from Daegwallyeong used in this study were daily mean temperature, precipitation, snowfall, mean relative humidity, and minimum relative humidity for 1972-2008, came from the Korean Meteorological Administration. From theses data, the annual and monthly precipitation, mean relative humidity, minimum relative humidity, snowfall, and mean temperatures were computed.

The number of fires are related to the climatic conditions of the year (Pausas, 2004). The correlations between the number of spring forest fires in the mountainous region of Gangwon-do and precipitation and snowfall accumulated from winter to early spring were analyzed using the meteorological data of Daegwallyeong and fire statistics. Because last forest fires of spring from 1989 to 2008 almost occurred on April and May, when the relationships were analyzed, the climate values during the previous December to March (i.e. from the winter before fire season to early spring) were used.

The lagged correlation were calculated where the annual number of forest fires were correlated with the prior seasonal precipitation. Several studies have found significant relationships between fire activity and antecedent climate conditions (Crimmins and Comrie, 2004; Pausas, 2004). Also, the correlations between the number of spring forest fires in the mountainous region of Gangwon-do and the number of precipitation days and relative humidity from winter to early spring were analyzed. Regressions and the F-test were used to validate the significance of relationships.

III. Results

1. The characters of forest fires in study area

Between 1989 and 2008, 202 forest fires burned a total of 618.7 ha were recorded in the study area. As is common with forest fires (Strauss *et al.*, 1989), most of the burned area was caused by a very small number of fires: there were only 8 forest fires (4.0%) larger than 10 ha that burned 427.0 ha (69.0% of the total area burned).

Figure 2 shows the trends of the number of forest fires and area burned in the mountainous regions of Gangwon-do for 1989 to 2008. The highest fire years were 1994 (22 forest fires), 2001 (21 forest fires), and, above all, 2000 (23 forest fires). But the number of forest fires between 1989 and 1993 were lower than 5 fires, and there was no occurrence of forest fire in 1990. The annual area burned during the period 1989-2008 shows a large interannual variability, with three clear peaks in 1993 (95.8 ha), 1996 (168.2 ha), and 2004 (100.2 ha).

The 3-h-accumulated fire occurrences in the mountainous region of Gangwon-do during the period 1989-2008 are displayed in Figure 3. A clear diurnal variation of forest fires emerges with its minimum after midnight and its maximum in the midafternoon. These two extreme phases of forest fires are separated by a sharp increase of fire occurrence that occurs after a phase of constant fire occurrence frequency from late night to early morning and a sharp reduction at night. In view of this diurnal variation, two fire occurrence regimes are identified: night – early morning and late morning – late afternoon. The diurnal variation of fire occurrence is almost out of phase with relative humidity. Also, the low rate of fire occurrence in the night-early morning regime may be attributed to the reduction of the

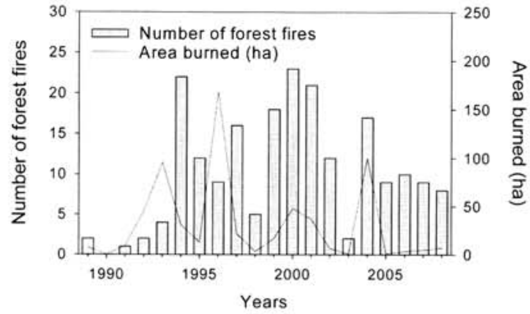

Fig. 2. Number of forest fires and area burned in the mountainous region of Gangwon-do during the period 1989-2008

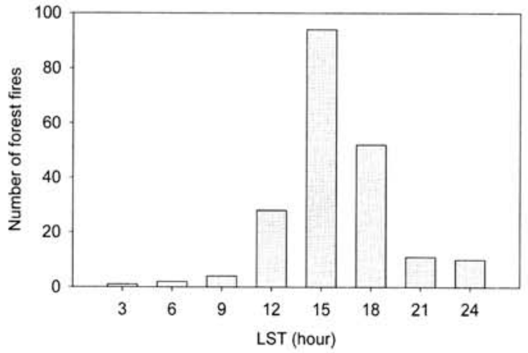

Fig. 3. Diurnal variations of fire occurrence (per 3 hours) in the mountainous region of Gangwon-do during the period 1989-2008. Respectively, 3, 6, 9, 12, 15, 18, 21, and 24 refer to the 3-h periods 0001-0300, 0301-0600, 0601-0900, 0901-1200, 1201-1500, 1501-1800, 1801-2100, and 2101-0000 LST

human activity.

Most (61.9%) of forest fires started during the spring fire season (March to May), and they accounted for 93.2% of the total burned area (Fig. 4). Within the general fire season, the highest fire month was April (35.1% in the total fires and 83.8% of the total area burned), the lowest fire season was summer. Because water is the most vital material to fight fire breakouts, water supplied by rain will certainly increase the moisture content of the environment and cut down the combustion efficiency so that fire outbreaks may be curtailed (Fosberg, 1971). Following the retreat of the east Asian summer monsoon in September, the intrusion of cold, dry

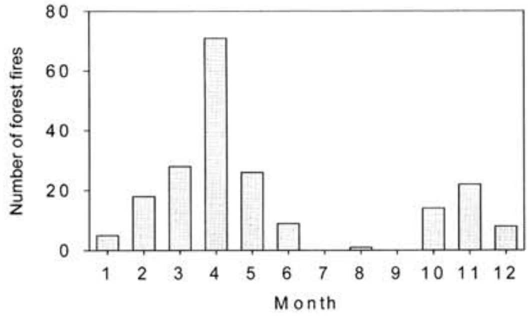

Fig. 4. Monthly number of forest fires in the mountainous region of Gangwon-do during the period 1989-2008

Siberian air creates a dry environment conductive to fire initiation. So the precipitation deficit during winter may facilitates fire occurrence of spring, whereas the reverse situation is true in summer. The trends in the number of forest fires and in the area burned during spring period was similar to that of the whole-year (data not shown).

2. Relationship between forest fires and climate

Forest fire occurrence is vitally affected by the amount of precipitation and moisture (Flannigan and Harrington, 1988). If precipitation is reduced, then potential fuels that are normally too wet to burn will dry more quickly and more often, thereby increasing the susceptibility of forest to burning.

The relationship between the number of spring forest fires and precipitation accumulated from winter to early spring (December-January-February-March, DJFM) is shown in Figure 5. The correlation between the number of spring forest fires in the mountainous region of Gangwon-do and precipitation accumulated during DJFM at the meteorological station of Daegwallyeong from 1989 to 2008 show a significant negative relationship. In wet winter and early spring, the number of spring fires tended to be small, while during dry winter and early

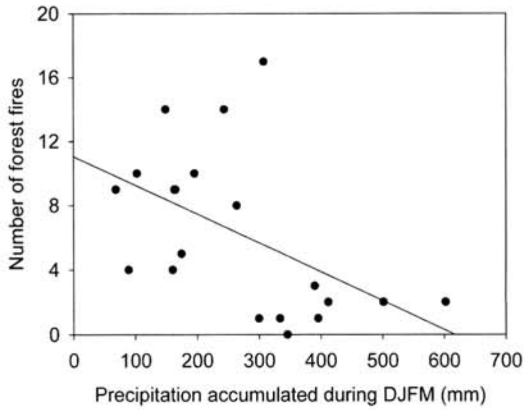

Fig. 5. Relationship between the number of spring forest fires in the mountainous region of Gangwon-do and precipitation accumulated during DJFM at the meteorological station of Daegwallyeong from 1989 to 2008 (DJFM, December-January-February-March)

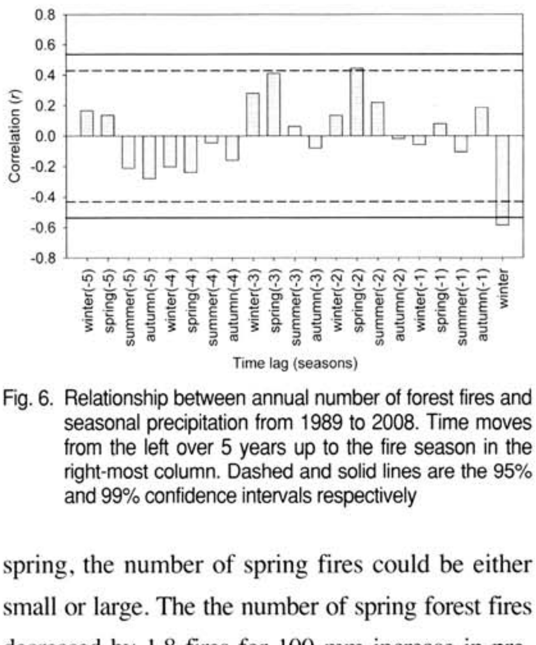

Fig. 6. Relationship between annual number of forest fires and seasonal precipitation from 1989 to 2008. Time moves from the left over 5 years up to the fire season in the right-most column. Dashed and solid lines are the 95% and 99% confidence intervals respectively

spring, the number of spring fires could be either small or large. The the number of spring forest fires decreased by 1.8 fires for 100 mm increase in precipitation accumulated during DJFM ($R^2 = 0.22, p < 0.05$).

The annual number of forest fires shows a significant negative correlation with winter precipitation at a time lag of 0 and a significant positive correlation with spring precipitation at a time lag 2 (Fig. 6). This suggests, first, the simultaneous relation between low winter precipitation and high number of forest fires and, second, a positive relation between spring precipitation and the number of fires two years later. In addition, the five peak in fire counts (1994, 1999, 2000, 2001, 2004) are strikingly coincident with above-normal spring precipitation in the second previous year. Consequently, the linear regression between the number of fires and spring precipitation in the second previous year was also significant (2.4 fires/100 mm, $R^2 = 0.15, p < 0.05$).

Long-term antecedent climate conditions are often overlooked as important drivers of forest fire variability. Fuel moisture levels and fine-fuel productivity are controlled by variability in precipitation at long timescale (months to years) before forest fire events (Swetnam and Betancourt, 1990; Westerling *et al*., 2002). The precipitation was correlated with the number of fires with some delay (2 years), suggesting that high precipitation may increase fuel loads that burn 2 years later. A positive relationship between fire and precipitation in prior years has also been reported in other studies (Crimmins and Comrie, 2004; Pausas, 2004). The precipitation and the number of fires are interrelated and each of these variables shows large interannual variability and thus, very low predictability. However, the fact that they are correlated suggests that chances of a high fire season can be predicted from the precipitation of the previous years.

The number of precipitation days during DJFM also show a significantly negative relationship with the number of spring forest fires (Fig. 7). Especially, while the number of days with precipitation ≧ 0.3 mm during DJFM show a significant relationship with the forest fire occurrences of spring, the number of days with precipitation ≧ 0.1 and 0.2 mm during DJFM show no significant relationship. This sug-

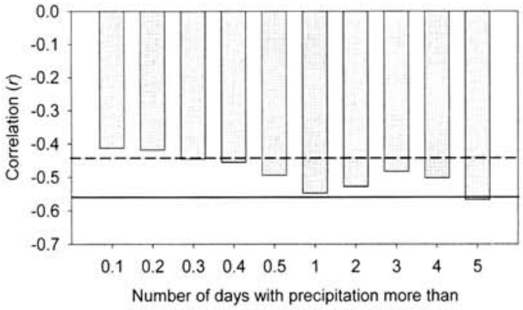

Fig. 7. Relationship between spring number of fires and number of days with precipitation more than 0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mm during DJFM (DJFM, December-January-February-March). Dashed and solid lines are 95% and 99% correlation significance levels respectively

gests the number of days with precipitation ≦ 0.2 have no influence on spring forest fires. Also, the number of days with precipitation ≧ 5.0 mm during DJFM have highly a significant negative correlation with spring number of fires. The number of spring forest fires increased by 2.5 fires for 10 days decrease in the number of days with precipitation ≧ 5.0 mm during DJFM ($R^2 = 0.32, p < 0.01$).

The number of spring forest fires was significantly related to relative humidity during DJFM (data not shown). That increased by 6.6 fires for 10% decrease in relative humidity during DJFM ($R^2 = 0.34, p < 0.01$). The relative humidity also has a significantly negative relationship with the burn velocity of forest fire (Fig. 8). The burn velocity of forest fire increased by 0.2 ha/hr for 10% decrease in the minimum relative humidity of fire occurrence day during spring ($R^2 = 0.04, p < 0.05$). The relationship between the minimum relative humidity and area burned was not significant. But large fires more than 30 ha occurred in the day when the minimum relative humidity was below 20%.

The relationship between the number of spring forest fires and snowfall accumulated during DJFM is shown in Figure 9. The number of spring forest

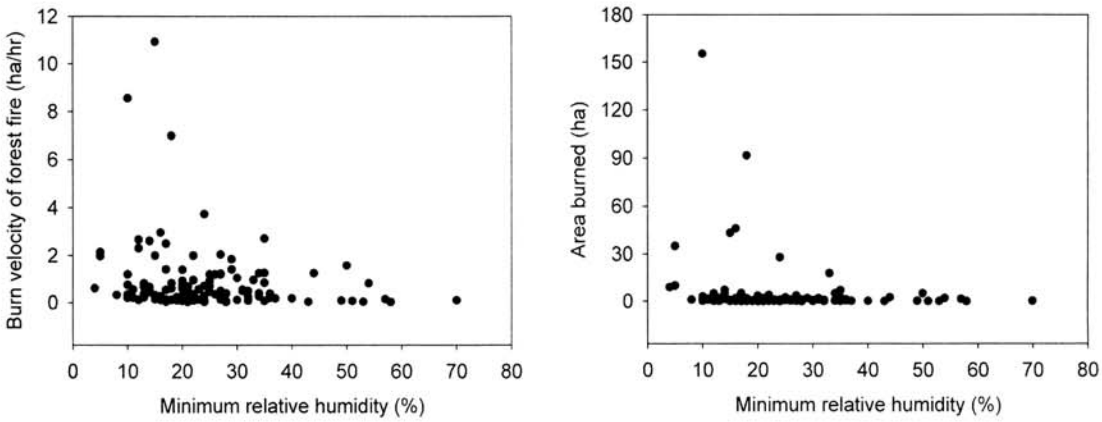

Fig. 8. Relationship between the minimum relative humidity of fire occurrence day and burn velocity of forest fire (left) and area burned (right)

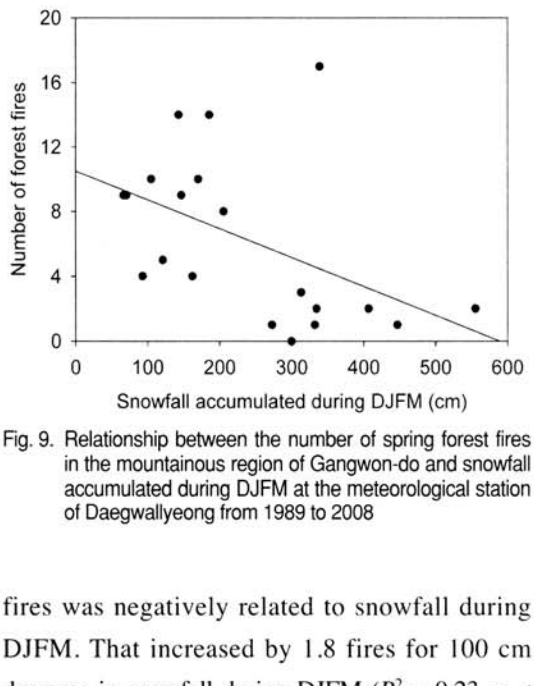

Fig. 9. Relationship between the number of spring forest fires in the mountainous region of Gangwon-do and snowfall accumulated during DJFM at the meteorological station of Daegwallyeong from 1989 to 2008

fires was negatively related to snowfall during DJFM. That increased by 1.8 fires for 100 cm decrease in snowfall during DJFM ($R^2 = 0.23$, $p < 0.05$).

IV. Discussion

In general, forest fires can be classed as either lightning-caused or people-caused. The ignition of lightning-caused fires, while dependant on cloud-to-ground lightning strikes, also depends on the moisture content within the organic layer of the forest floor where a fire can smoulder until surface fuels become dry enough to sustain surface spread. People-caused fire occurrence generally depends on the moisture conditions of the fine fuels on the surface of the forest floor (Cunningham and Martell, 1973). Fine fuels are the cured needles and twigs and other small diameter woody or grassy materials lying on the forest floor. These types of forest floor materials are key components in the propagation of surface fire spread and their moisture content plays a critical role in determining the sustainability of an ignition.

Since moisture in the fuels on the forest floor is dependant on past and recent air temperature and rainfall, as well as a number of other factors, potential changes in these elements expected to accompany climatic change could influence forest fire activity (Weber and Flannigan, 1997; Soja *et al*., 2006). Analysis of the meteorological record for Daegwallyeong showed increases in temperature and precipitation and decreases in relative humidity

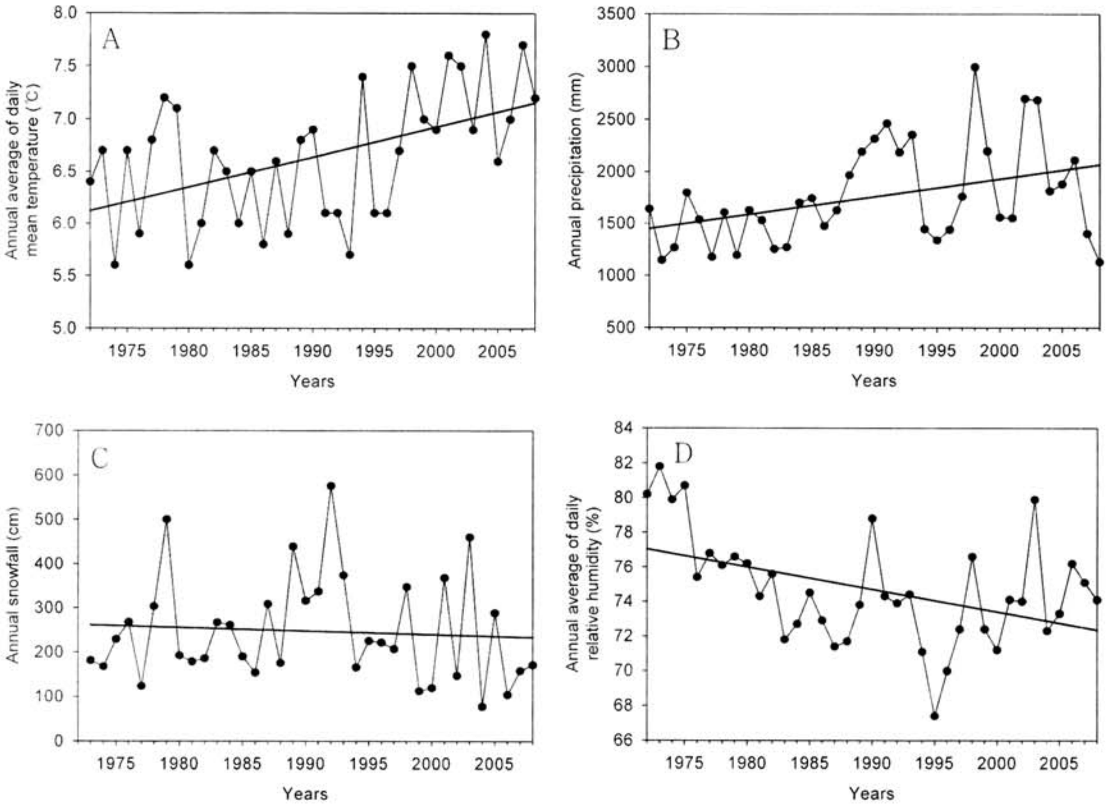

Fig. 10. Annual mean values of daily mean temperature (A), daily precipitation (B), daily snowfall (C), and daily relative humidity (D) at the meteorological station of Daegwallyeong from 1972 to 2008

and snowfall between 1972 and 2008 (Fig. 10). However, the increase in annual precipitation was the result of the increase in summer (June to August) precipitation (99.74 mm per decade, $p < 0.05$), and precipitation in spring and winter were no change. Thus, the climate in winter and spring bas become warmer and drier during 1972-2008 as a result of increases in temperature and decreases in humidity. During the last 20 years, fires in dry years tended to occur more frequent than fires in wet years (Fig. 5). The data suggest that if the current climatic trends remain constant, fuel conditions will become drier each year and, as a consequence, the risk of forest fires will increase. Increasing fire danger under changing climatic conditions has been predicted in many ecosystems (Stocks *et al*., 1998; Williams *et al*., 2001; Pausas, 2004). Nevertheless, the number of forest fires and burned area in study area show no increasing trend (Fig. 2). Since the incidence of forest fires depends on many factors, clearly it is difficult to make such an assertion simply on the basis of meteorological data alone.

Among other factors affecting fire incidence, human activity is of primary importance. Humans are the main cause of fire initiation in Korea (Lee *et al*., 2001). Contributions to fire occurrence by the lightning-cause were only 1.5 percent in mountainous region of Gangwon-do from 1989 to 2008. Humans also have the influence, through fire suppression. In Korea, fire suppression efforts have increased since the early 1970s, whereas rural activities have decreased (Lee, 2006). Also, forest continuity and biomass increased, and these changes enhanced th likelihood of fire occurrence and severity. It is difficult to obtain precise figures on the number and distribution of ignition causes or in land-use modifications. Clearly, these changes confound the relationship between meteorological fire hazard and fire activity.

V. Conclusions

Fire plays a critical role in the maintenance of healthy forest ecosystems and is strongly regulated by climatic conditions. This study identified the fire climate variables strongly associated with occurrence of forest fires in the mountainous region of Gangwon-do by analyzing the correlation between the number of forest fires in spring and precipitation, number of precipitation days, relative humidity, and snowfall before fire season.

The 202 forest fires burned a total of 618.7 ha were recorded for 1989-2008 in the mountainous region of Gangwon-do, and most of the burned area was caused by a very small number of large fires. The total fire occurrence showed a maximum peak in April and a minimum peak in summer. The number of forest fires during spring (March-April-May) accounted for 61.9% of the total fires. Two regimes are identified in the diurnal variation of fire occurrence: night – early morning and late morning – late afternoon. These two regimes are separated by a increase of fire occurrence in the morning and a decrease of fire occurrence at night. The diurnal variation of fire occurrence is almost out of phase with relative humidity.

The number of spring forest fires in the mountainous region of Gangwon-do showed a significantly negative relationship with precipitation accumulated from winter to early spring (December-January-February-March, DJFM), that is, when the winters before fire season were dry, the fire occurrence was higher than in wet winters. The annual number of forest fires was significantly correlated with spring precipitation for a time-lag of 2 years, suggesting that high precipitation during spring may increase fuel loads that burn 2 years later. The number of spring forest fire also had a significantly negative relationship with the number of precipitation days during DJFM. While the number of days with precipitation $\geqq$ 0.1 and 0.2 mm during DJFM showed no significant relationship, the number of days with precipitation $\geqq$ 0.3 mm was significantly correlated with the forest fire occurrences of spring. Therefore, the more precipitation and the number of days with 0.3 mm more at the least during DJFM, the less forest fire will occur in spring. The fire occurrence of spring also showed a significantly negative relationship with relative humidity and snowfall during DJFM. In particular, large fires more than 30 ha occurred in the day with minimum relative humidity below 20%.

In this study, precipitation, number of days with precipitation, relative humidity, and snowfall were important factors on prediction of future fire activity. But the period of data used in this study was too short to predict the fire occurrence, and other factors related to forest fire also need to be considered. Consequently, the relationship between forest fires and climatic conditions need to be studied using longer forest fire statistics to predict more accurately. Also, the impact of climate change on forest fire occurrence should be studied more accurately in the future.

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