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ARTICLE

A Study on Comparative Analysis of Fire Weather Risk Index Models for Wooden Cultural Heritage

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Abstract

Globally, research on fire weather indices (FWIs) has been conducted to establish fire risk management systems at national or regional scales. In this study, 16 existing FWIs were compared and analyzed, and the five most suitable cases were evaluated to confirm their applicability in Korea. Meteorological factors applied to 16 FWIs collected and surveyed around the world including wind, temperature, relative humidity, effective humidity, precipitation, vapor saturation pressure, potential evapotranspiration, and dew point. The estimated risk levels based on FWI values are generally divided into five grades: As a result of applying five FWIs to Korea's forest area, Korea's fire weather risk was found to be 2 to 3 grades lower than in countries where this index was introduced, and the fire season in forest areas was also found to be different. A statistically significant correlation was found between the risk index based on forest fire statistics such as wind speed, relative humidity, and effective humidity and meteorological factors, but temperature did not show a significant correlation.

Keywords: Fire Weather Index, Wooden Cultural Heritage, Fire Risk Map, Risk Assessment, Temple

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1. Introduction

According to statistics on fires that occurred in traditional wooden temples over the past five years (2016 to 2020), a total of 250 fires occurred, 7 people were injured, and property damage amounted to approximately 4.5 billion Korean won. The most common cause of fire was carelessness (106 cases), followed by electrical causes (67 cases). Fire weather is among the major natural disasters as it not only destroys forests but threatens people's lives and properties along with cultural heritages.

Fire weather can have many serious negative impacts on human life & safety (Viegas, 2002), health (Schwela et al., 1999; Heil and Goldammer, 2001; Kunii et al., 2002; Sastry, 2002), regional economies (e.g., Glover and Jessop, 1999), and global climate change (Crutzen and Goldammer, 1993; Kasischke and Stocks, 2000). In terms of drivers of fires, climate change, land utilization, and forest development are main factors to increase the frequency and intensity off fire weather in numerous regions of the world. For example, the climate during the recent decades (increase of fire season length, more frequent occurrence of long hot and dry periods) has been attributed to substantially accelerated fire regimes in some Asian regions (Peter F. Moore, 2013). A specific feature of current fire regimes is a wide distribution of mega- or catastrophic fires that envelop vast territories, have a very high intensity, often out of control, and provide extremely high damages in terms of social, economic, and cultural values. Current predictions of future fire regimes in the Northern Hemisphere (Stocks, Flannigan, Turetsky, Tchebakova, etc.) indicate at two to three times increase in the extent and severity of fire weather by the end of the current century. In order to reduce the occurrence of natural fires and subsequent damages, special systems of fire protection need to be developed. Among other activities, it is essential to strengthen existing methods of protection from fire and to in advance decrease risk factors. To this end, Fire Weather Danger Rating System (FWDRS) can be highly instrumental. Among many factors used in the system, weather elements are the most influential. Some of the Fire Weather Index (FWI) used around the world includes Angström Index (Skvarenina et al. 2003), Fuel Moisture Index (FMI, Sharples et al., 2009; Liu et al., 2010), Nesterov Index (Nesterov, 1949; Willis et al., 2001), WBKZ-M68 (Käse, 1969), Thernthwaite Index (Thornthwaite, 1948; Amoriello and Costantini, 2003), and The Canadian Fire Weather Index (CFWI, Van Wagner, 1985). The CFWI is widely used in different countries providing, e.g., Web-GIS based information in Canada, Indonesia and other countries. The index was developed upon the data of fuel moisture contents in the Arctic Zone and has been found to be particularly good at warning against mega fires. Fire danger is directly related with fuel moisture content (FMC), which is highly affected by climate and fuel conditions (Sharples et al., 2009). Fuel moisture can be affected by slowing the rate of fuel combustion, through increasing ignition time, decreasing fuel consumption and increasing particle residence time (Nelson, 2001).

Many studies have been carried out concerning the correlation between climate and fuel conditions in order to determine the danger of fire weather. Forest fire danger index developed around the world mostly uses meteorological factors and partly fuel and topographical factors. Fire Weather Danger Index models can be broadly split into two categories: 1) fire danger evaluation by analyzing fuel humidity and 2) fire danger evaluation by analyzing drought index.

A number of recent studies of the correlation between fire weather and fuel humidity have shown good empirical relations between FMC and satellite-derived variables in several ecosystems (Paltridge and Barber, 1988; Chladil and Numez, 1995; Chuvieco et al., 1999; 2003). FMC for grasslands was more efficiently estimated than other fuels

(Paltridge and Barber, 1988; Hardy and Burgan 1999), because water variations in grasslands have a greater influence on other variables that critically affect plant reflectance (such as chlorophyll content or leaf area index) and are more sensitive to seasonal variations than shrubs or trees. Experiences with shrubs have been less successful, with trends varying by species analyzed (Fire Paradox, 2010). In studies of the correlation between fires and drought index, drought indices such as KBDI (Keetch-Byram Drought Index) and Palmer Drought Index (PDI) have been used to measure drought for fire weather risk assessment. KBDI, which is now used for forecasting the occurrence risk of forest fire by US Forest Service, was designed based on mathematical models for predicting the likelihood of forest fire considering soil moisture and other conditions related to drought (Keetch & Byram, 1968). The Palmer Drought Index is based on a supply-and-demand model of soil moisture (Wayne C. Palmer, 1965) while the US Forest Service's Wildland Fire Assessment System offers information on soil drought.

As stated above, various FWI's have been developed by using FMC and drought index, and they are widely applied. In this context, the goal of this study is to compare and evaluated the factors of 16 released FWI models, and to evaluate 5 of them in terms of their applications for South Korea. Finally, this study aims to see if the existing FWI models can be used regardless of weather conditions and fuel characteristics that vary depending on nation and region, thereby improve their future applicability.

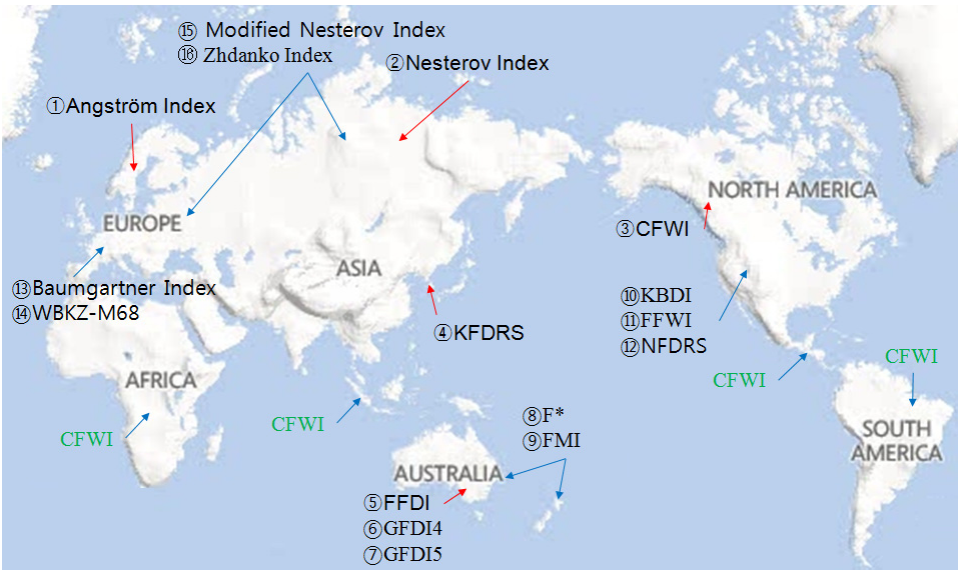

Fig. 1. Distribution map of the development and use of FWI models throughout the world

2. Analysis of FWIs

2.1 Fuel Moisture Contents and FWI

GFDI4 (McArthur, 1966) and GFDI5 (McArthur, 1977) applies wind, dry-bulb temperature, relative humidity and degree of grass curing as the basic factors of fire danger index to grassland. GFDI5 applies FMC in combination with dry-bulb temperature, relative humidity, degree of grass curing, and fuel weight (t/ha). Both GFDI4 and GFDI5 divide fire danger index into five categories. Fine Fuel (CFWI), Fuel Model (NFDRS) and Grassland (GFDI4, GFDI5) may all

be used to evaluate forest fire danger indices based on fuel humidity. The Korea Forest Fire Danger Rating System (KFDRS) consists of three, 10－scale indices: daily weather index (DWI), fuel model index (FMI), and topography model index (TMI). DWI represents the meteorological characteristics, such as effective humidity, temperature and wind speed, and is adapted to local conditions through the use of one of eight logistic regression models (Won et al, 2010). The Canadian Fire Weather Index (CFWI, Van Wagner, 1987), among those, calculates FMC of the three fuel layers in Canada's coniferous forests, which are represented as Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC). Initial Spread Index (ISI), Build Up Index (BUI) and Fire Weather Index (FWI) are then calculated based on the three codes. FWI is divided into six phases, which are used in Canada and Southeast Asia including Indonesia, and can be used as a danger index for Global Mega Fire. U.S. NFDRS (Deeming and others 1972), which has been up and running since its development, has numerous fire danger information such as Fire Weather Information, Fuel Moisture Content, Models of Fire Characteristics and Models of Fire Occurrence. Fuel Moisture Contents, which is one of the study's subjects, calculates the whole FMC based on Equilibrium Moisture Content (ECM). The EMC, itself a computed value, represents a steady state moisture content of dead woody material. This steady state is achieved under constant conditions for a sufficiently long adjustment period. Steady-state conditions do not occur under normal circumstances and, therefore, do not represent the woody moisture contents. On the other hand, EMC can be derived from dry bulb temperature and relative humidity by calculating the equilibrium moisture content (ECM). Equations of ECM are the regression equations development by Simard (1968) on the basis of tables in the Wood Handbook (U.S. Forest Products Laboratory 1955, revised 1974). NFDRS considers two major groups of fuels; live and dead. Models of Live-Fuel Moisture are further classified into annual herbaceous, perennial herbaceous, and lesser woody plants (shrubs and young trees). Models of Dead Fuel Moisture is applied to 1, 10, 100, and 1000 hour time lag classes and wet or ice covered regions. NFDRS uploads danger map information in 1km*1km lattice in the Internet on real-time across the United States.

2.2 Drought Index and FWI

Angströn Index (Willis et al., 2001) is currently being used throughout the Scandinavia Peninsula and is an aridity index based on temperature and relative humidity, divides fire weather danger index into five categories in the Scandinavia region. Baumgartner Index uses potential evapotranspiration and precipitation to set danger index into five categories. It is widely used in the Scandinavia region and Germany. F* (Sharples et al., 2009), which is computed via Wind, Temperature and RH, is divided into five categories and used in Australia and New Zealand. FFDI (Forest Fire Danger Index, Nobel et al., 1980) divides fire weather danger index into five categories by using wind speed, dry-bulb temperature and relative humidity factors. It is widely used in eastern Australia. FMI (Fuel Moisture Indices, Sharples et al., 2009) calculates FMC of eucalypt litter as temperature and relative humidity. Its index range is 0~30. Average absolute error of FMI's interaction formula is 0.2%. Zhdanko (1965) suggested a recurrent index of potential fire weather risk for the warm snow-free period of the year (Groisman et al. 2005a, b). Zhdanko index is widely used in the Russian fire-rating system along with Nesterov and Modified Nesterov Index. Nesterov index (1967) was devised as the interaction formula for date, average temperature and dew point temperature from the rain day with a precipitation exceeding 3mm. whitch also was used in the former Soviet Union. A modified version of the Zhdanko index (Groisman et al., 2005a, b) is currently widely used in Russia, and it is based on a reduction factor similar to that used by Zhdanko

index. Both models divided danger index into five categories. WBKZ-M68 is used in the north eastern part of Germany. WBKZ-M68 divides fire danger level into four levels by using vapor saturation and temperature (Käse, 1969). KBDI is a cumulative estimate of moisture deficiency based on meteorological parameters and an empirical approximation for moisture depletion in the upper soil and surface litter levels (Keetch and Byram, 1968; Janis et al., 2002). KBDI is a stand-alone index that can be used to measure the effects of seasonal drought on fire potential (Roads et al., 2005).

Table 1. Physical properties of the FWIs

Fire Weather Indices	Developed by (year)	Country (Region)	Using data									Index Range(Level)
			Weather							Forest (Fuel)	Topography	
			W	D	T	RH	R	V	E			
Drought Index												
Angström Index	Willis et al. (2001)	Sweden (Scandinavia)			○	○						<4 ~ >4 (5)
FMI	Sharpleset al. (2009)	Australia & New Zealand			○	○						0~30
F*	Sharpleset al. (2009)	Australia & New Zealand	○		○	○				-	-	< 61 ~ 61< (5)
FFDI	Nobel et al. (1980)	Australia	○		○	○						0~100 (5)
FFWI	Fosberg (1978)	USA	○		○	○						
WBKZ-M68	Käse (1969)	Germany			○			○				501~7,000 (4)
Baumgartner Index		Germany					○		○			< -12 ~ 41 < (5)
Keetch-Byram Drought Index	Keetchand Byram(1968)	USA	○		○	○	○				○	0~800 (5)
Nesterov Index	Nesterov (1949)	Russia, Austria		○	○	○	○	○				< 300 ~ >10,000 (5)
Modified Nesterov Index	Groismanet al. (2005)	Eurasia		○	○		○					100 ~ >10,000 (5)
ZhdankoIndex	Zhdanko (1965)	Russia		○			○					
Fuel Humidity												
GFDI4	McArthur (1966)	Australia	○		○	○				○		0~200 (5)
GFDI5	McArthur (1977)	Australia	○		○	○				○		0~200 (5)
KFDRS	KFRI (2003)	Korea	○		○	○				○	○	0~100 (4or 5)
CFWI	Van Wagner (1985)	Canada and Global	○		○	○	○	○		○		<2, >30 (6)
NFDRS	Deeming et al. (1972)	USFS	○	○	○	○	○	○		○	○	A multiplicity index

Remarks: FMI : Fuel Moisture Indices, F*: Fire Danger Index, CFWI: Canadian Fire Weather Index, GFDI: Grassland Fire Danger Index, KFDRS: Korea Forest Danger Rating System, NFDRS: National Fire Danger Rating System, W: Wind, D: Dew point, T: Temperature, RH: Relative Humidity, R: Rainfall, V: Vapor saturation or pressure, E: Potential Evapotransportation

3. Application of 5 FWIs to Rep. of Korea

As shown in Table 1 and Fig. 1, FWI's have been developed in a national and regional level and they are being widely and frequently used. Since most indices were developed targeting a specific nation or a specific region that represents a climate zone (a number of regions where similar climate characteristics appear), it shall be investigated if the risk indices work without any problem when they are applied to other climate zones or regions. For this, five regional indices (Angström index, Nesterov Index, CFWI, KFDRS, and FFDI) were applied to the fire weather environment of South Korea, and the corresponding indices were compared and evaluated.

The Angström index (I), is one of the simple drought indices developed using temperatures and relative humidity (Willis et al., 2001; Skyarenina et al., 2003). This index has been compared with the Nestrov and Baumgartner indexes for two large forest fire events at the Slovak paradise National Park, which revealed that the Angström index was the most sensitive in fire occurrence risk prediction (Skyarenina et al., 2003):

$$I = (R/20) + [(29 - T)/10] \tag{1}$$

where, R is Relative humidity (%) and T is temperature (°C).

The Nesterov Index (NI) was developed by V.G. Nestrov in 1967. The Nesterov Index is an empirical drought index widely used in Russia. The index uses synoptic daytime data of temperature, humidity, and daily precipitation (Groisman et al., 2005a, b). The index was derived as an empirical function reflecting the relationship between fire and weather based on historical data (Venevsky, 2002), and is calculated as the following(Willis et al., 2001; Skvarenina et al., 2003):

$$NI = \sum_{i=1}^{W} T_i x (T_i - D_i) \tag{2}$$

where, W is number of days since last rainfall > 3 mm, T is mid-day temperature (°C), D is dew point temperature (°C).

Its computation begins on the first spring day when the height of temperature is above freezing, after snow melting, and continues until the rainfall of 3 mm. The total is calculated for positive temperatures for a sequence of days with precipitation less than 3 mm. Rainfall above 3 mm resets the index NI to zero. It is a cumulative index and reflects drying potential for fuels. It was comparatively tested with other indices (Keetch-Byram drough index, Modified Nesterov and Zhdanko index) over northern Eurasia (Groisman et al., 2005b; Groisman et al., 2007), by testing their values versus forest fire statistics as well as with Keetch-Byram drought index in East Kalimantan, Indonesia (Buchholz and Weidemann, 2000). In both cases it was proved applicable and a useful tool for early warning.

The CFWI was developed for the prediction of fire weather risk in response to weather data in Canada. The CFWI requires daily temperature, RH, wind speed, and 24-hour accumulated rainfall inputs for its calculation (Van Wagner, 1987). CFWI is composed based on three fuel moisture codes, the drought code (DC), duff moisture code (DMC), and the fine fuel moisture code (FFMC), and three behavioral indices which are the buildup index (BUI), initial spread index (ISI), and fire weather index (FWI). All indices are then combined into the FWI which gives estimation about the overall Fire danger situation and is used to classify and communicate fire danger. FFMC represents the moisture of the

uppermost layer of litter in a pine tree, approximately 1.2 cm deep. FFMC is in itself based on wind speed, RH, precipitation, and temperature data as calculated in Equation 3. DMC represents the moisture in the 7 cm deep layer below the fine fuel layer, assumed to be a layer of loosely compacted organic material. DMC is based on RH, precipitation, and temperature data as calculated in Equation 4. DC represents the moisture in a layer of compact organic matter extending 18 cm below DMC layer. DC is calculated only from rainfall and temperature data by Equation 5. ISI is a numerical rating of the combination of wind and the FFMC that presents the expected rate of spread. BUI is a numerical rating of the total amount of fuel available for combustion that combines the DMC and the DC. CFWI is thus a numeric rating of fire intensity based on ISI and BUI. This indicates the fire intensity by combining the rate of spread with the amount of fuel being consumed (De Groot, 1987).

$$FFMC = 595 \times (250 - m)/(1472/m) \tag{3}$$

where m is the fine fuel moisture content after drying

$$P = P_0(P_r) \times K \times 100 \tag{4}$$

where P is the new DMC, P_0 is the previous day DMC, P_r is the DMC after rain and K is the log drying rate in DMC.

$$D = D_0(\text{or } D_r) + 0.5 \times V \tag{5}$$

where D is the new DC, D_0 is the previous DC, D_r is the DC after rain and V is the potential evapotranspiration.

The KFDRS was developed by applying statistical analysis techniques to suit the characteristics of each region through correlation analysis between meteorological factors and forest fire occurrence patterns. The KFDRS was estimated using a logistic regression model with forest fire occurrence by region as the dependent variable and meteorological factors as the independent variables. Formulas for nine administrative districts' models of KFDRS have been presented as shown in Table 2. In comparative analysis of forest fire occurrence statistics and prediction models, the accuracy of 75.83% has been (Won et al., 2010).

Table 2. Regional Model of forest fire occurrence probability model using logistic regression analysis in South Korea (Won et al., 2010).

Regions	Models	PV (%)
Gyeonggi	$[1+\exp\{-(2.507+(0.112 \times T_{max})-(0.061 \times RH)-(0.123 \times W_{mean}))\}]^{-1}$	73.6
Gangwon	$[1+\exp\{-(1.932+(0.109 \times T_{max})-(0.047 \times RH)-(0.057 \times EH)+(0.646 \times W_{mean}))\}]^{-1}$	80.7
Gyeongnam	$[1+\exp\{-(4.713+(0.076 \times T_{max})-(0.055 \times RH)-(0.023 \times EH)-(0.572 \times W_{mean}))\}]^{-1}$	74.4
Gyeongbuk	$[1+\exp\{-(2.030+(0.052 \times T_{max})-(0.062 \times RH)+(0.038 \times EH)-(0.320 \times W_{mean}))\}]^{-1}$	68.7
Jeonnam	$[1+\exp\{-(1.931+(0.087 \times T_{max})-(0.055 \times RH)-(0.014 \times EH)+(0.329 \times W_{mean}))\}]^{-1}$	70.1
Jeonbuk	$[1+\exp\{-(-0.281+(0.127 \times T_{max})-(0.042 \times RH))\}]^{-1}$	73.5
Chungnam	$[1+\exp\{-(-0.188+(0.113 \times T_{max})-(0.041 \times RH)+(0.182 \times W_{mean}))\}]^{-1}$	70.6
Chungbuk	$[1+\exp\{-(-0.857+(0.127 \times T_{max})-(0.066 \times RH)+(0.038 \times EH))\}]^{-1}$	72.8
Jeju	$[1+\exp\{-(-6.224+(0.040 \times T_{max})+(0.399 \times W_{mean}))\}]^{-1}$	98.1

where, T_{max} is the maximum temperature, RH is relative humidity, EH is effective humidity, W_{mean} is the mean of wind velocity and PV is predict value.

FFDI was derived to assess forest and grassland fire danger ratings in southeastern Australia. According to Nobel et al. (1980), FFDI can be expressed as:

$$FFDI = 2\exp(-0.45 + 0.987\ln(D) + 0.0338T - 0.0345H + 0.0234U) \quad (6)$$

where T and H are temperature and relative humidity as before, U is average wind speed and D is the drought factor, which ranges from 1 to 10, where D=10 indicates maximum fuel availability.

In conclusion, the risk index of the five FWI models can be classified based on the levels of fire weather risk as shown in Table 3.

Table 3. Risk levels of the five selected FWI models

Levels / Models	Low ←		Fire Risk		→ Extreme
	1	2	3	4	5
Angström index	> 4	4.0 - 3.0	3.0-2.5	2.5-2.0	< 2.0
Nesterov Index	< 300	300-1000	1000-4000	4000-10000	> 10000
CFWI	0-4.5	4.5-10.5	10.5-18.5	18.5-	
KFDRS	0-20	20-40	40-60	60-80	> 80
FFDI	0-5	5-12	12-24	24-50	50-100

The five FWI models were applied to the Gyeongbuk region of South Korea, using the last 8-year weather data (2005-2012). As displayed in Fig. 2, Gyeongbuk has the highest frequency of fire outbreaks in the Forest od Rep. of Korea. According to the weather data, the average meteorological observation area of this region is approximately 33km × 33km. The weather data was based on the annual average of 8-year daily observation data presented by the Korea Meteorological Administration (KMA).

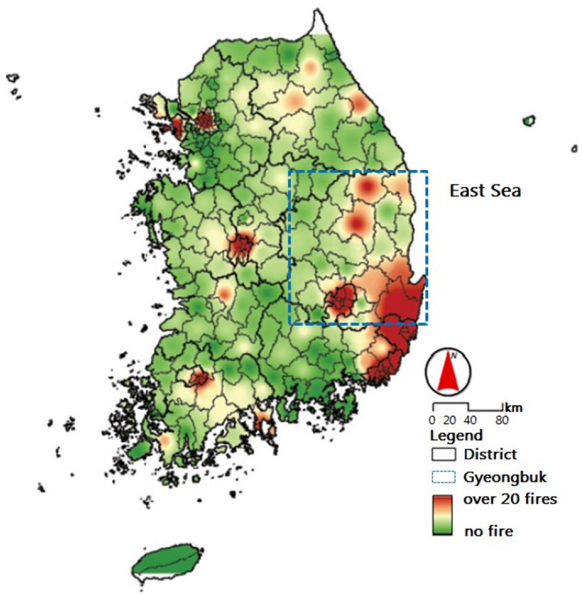

Fig. 2. Regional distribution of forest fire occurrence in South Korea (8-year average, 2005-2012), and Gyeongbuk to which the five FWI models will be applied

4. Results

When applying the five FWI models to Gyeongbuk, South Korea, daily risk index for each model was displayed with a certain pattern of changes as shown in Fig. 3. As for changes of the models' risk indices, first, Angström index (a) showed lower risk index value in summer than the one from fall to spring, which means higher forest fire risk is posed during summer. Nesterov index (b) showed higher risk index from May through July (the highest) to October than any other period of the year. CFWI (c) showed higher risk level in January and around May and June. KFDRS (d) showed higher risk index in 3 months from February to April. FFDI (e) showed lower risk index overall, and no significant deviations were observed in the monthly risk index.

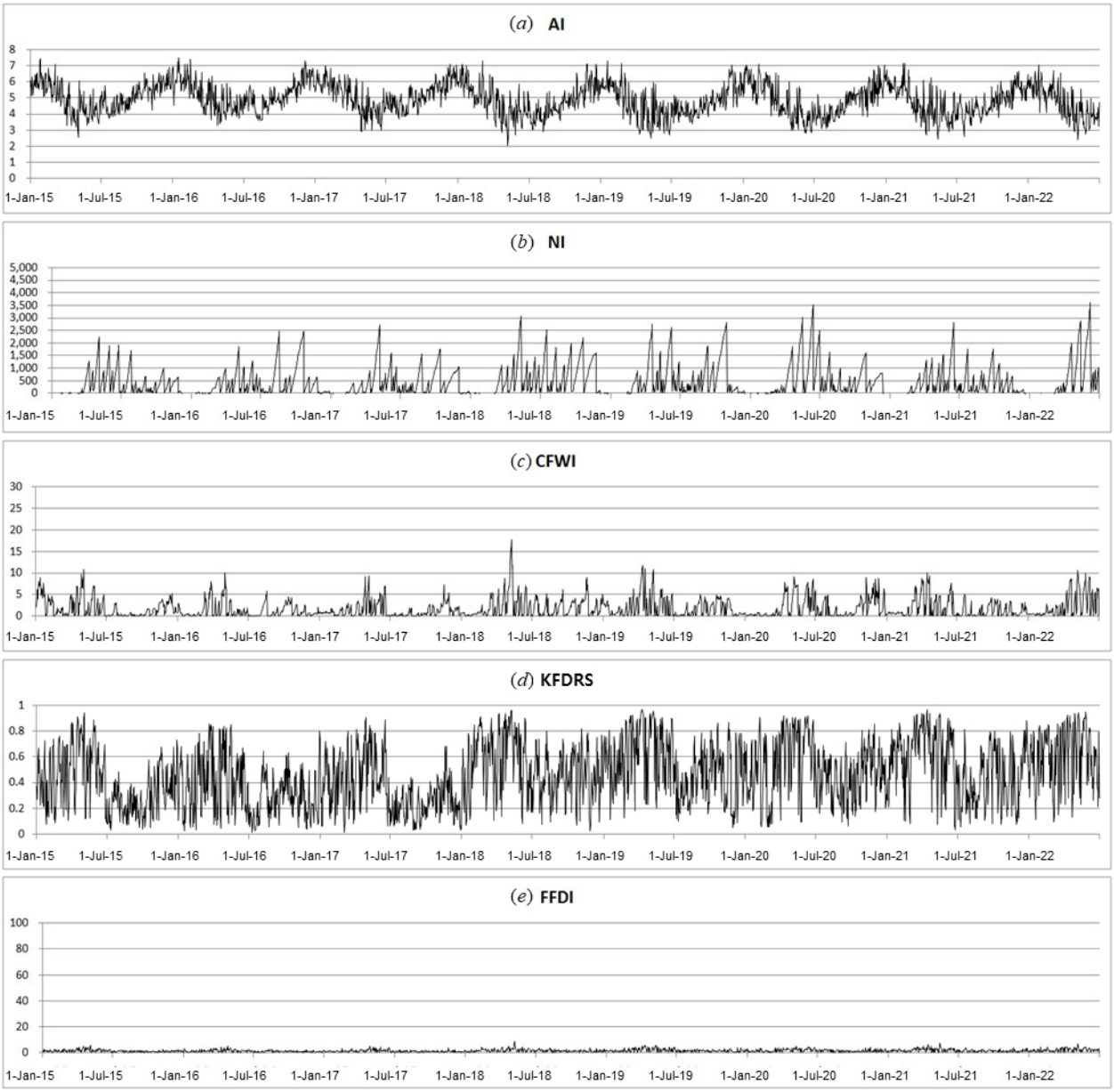

Fig. 3. Time series of the five FWI models, Jan 2005 ~ Dec 2012, Gyeongbuk Republic of Korea. (a) Angström index, (b) Nesterov index, (c) CFWI, (d) KFDRS, (e) FFDI

As for the average monthly risk level for eight years, only KFDRI showed a higher risk index in spring and fall, which are the seasons considered to be the forest fire-danger periods. AI, NI, CFWI, and FFDI assessed the forest fire risk lower than Risk Level 2 and in those indices, no significant difference was shown between spring and summer (spring is considered to be fire-danger period, but summer is not). The forest fire risk levels of Gyeongbuk assessed by the five FWI models are shown in Fig. 4.

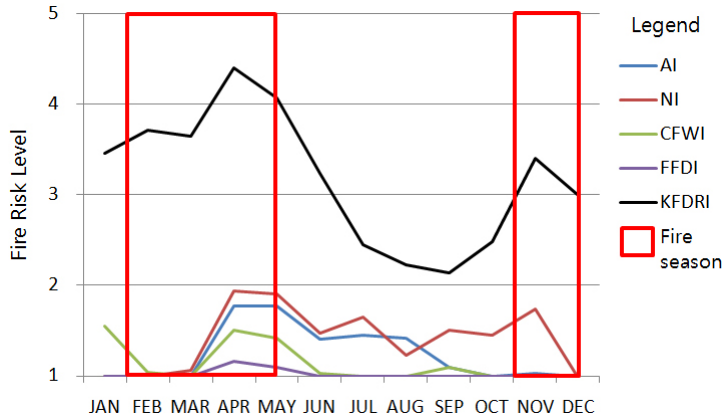

Fig. 4. Monthly assessment results by five FWI models (8yrs average based on data for 2015 to 2022)

5. Conclusions

This study examined sixteen FWI models developed and used for monitoring fire weather risk. The sixteen FWI models were divided into two groups based on fuel humidity and drought. Out of the sixteen models, fuel humidity-based models were: GFDI4, FDI5, KFDRI, CFWI, and NFDRS. To assess fire weather risk in the forest of the Gyeongbuk region in South Korea, AI, NI, CFWI, KFDRI, FFDI models were selected and examined. The results revealed that all models developed outside of South Korea failed to produce suitable results for determining fire-danger periods. The models assessed fire weather risk to the forest to be much lower than the actual risk posed and the fire weather rates were estimated higher in summer than in spring. This might be due to the coefficients of factors used for the development of most FWI models being determined based on empirical data and regression evaluation of regional weather, fuel conditions, and forest fires. In South Korea, unlike the U.S., Canada, Australia, Russia, and European and Southeast Asian countries, forest fires occur more frequently during early spring than any other seasons due to Monsoon, dry and strong seasonal winds; however, less fire weather risk is posed in hot and humid summer. Northeast Asian countries like Mongolia, China, and Japan, which lie in the same latitude range as South Korea and are affected by dry seasonal winds in spring, experience more forest fires during spring than in any other period.

Therefore, it is considered that when applying national or regional FWI models to a certain nation or a region that has different fire environments, relevant assessment, and verification needs to be performed, though for the nations or regions that have the same or similar fire environment, the applicable FWI can work properly. Thus, in order to identify the risk of fire weather more precisely, further studies are required on how to effectively use FWI for each region and how to develop the FWI model with expanded applicability through further fire weather analysis and numerical

analysis. Such studies would significantly help to develop FWI models with enhanced applicability from a national, and regional level to a global level.

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