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Development of a Woody Fuel Moisture Prediction Model Following Rainfall Events for a Deciduous Forest in Yeongdong Region of Korea

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Moisture content of woody fuel is an important indicator of fire risk, and thus can be effectively used for fire management. Most forest fires in Korea occur during spring in Korea, when low fuel moisture condition is combined with strong westerly dry Foehn wind. To better understand the fuel moisture dynamics during this season, we developed a fuel moisture prediction model for a deciduous forest stand in Yeongdong region in Korea to predict the moisture content of aboveground woody fuel after significant precipitation events (>5.0 mm). The model was based on changes in moisture content of woody debris for several fuel size classes based on their diameter (<0.6 cm, 0.6–3.0 cm, 3.0–6.0 cm, and >6.0 cm), measured in the spring of 2008.

Results indicate that fuel moisture content dropped more rapidly in smaller fuels (time until high fire risk moisture level reached after 3 days since precipitation event for fuel size class <0.6 cm, and 6 days for 0.6–3.0 cm) and in stands with lower canopy cover. Our model showed reasonable performance in representing the changes in fuel change, and was successfully validated against 2009 data.

Key words: forest fire, fuel moisture, forest density, deciduous forest, prediction model

INTRODUCTION

Most forest fires in Korea occur during spring season: in the last several decades (1975 to 2010), 60% of all forest fires and 25 of the 57 large forest fire events (>1000 ha) occurred during the 3 month period between February 15 and May 15 (Korea Forest Service, 2010). In Yeongdong region (east of Taebaek mountain range) of Korea, dry warm Foehn wind is created by Westerlies travelling over the Taebaek mountain range, which dries out woody fuel and results in conditions ideal for successful ignition and rapid spread of forest fires in the forested area (Korea Forest Service, 2010).

Many researches in the United States and Canada considered moisture content of forest fuel as one of the most important factors for evaluating risk of forest fire, especially as a strong driver in successful fire ignition and subsequent spread (Van Wagner, 1975; Stocks, Lawson *et al*., 1989). For example, in the Canadian Forest Fire Danger Rating System (CFFDRS), a national system for rating the risk of forest fires in Canada, Fine Fuel Moisture Code (FFMC) is one of the important components of the Canadian Forest Fire Weather Index (FWI) System, which is widely used for calculating fuel moisture level and the resulting flammability of fine fuel, based on consecutive daily observations of temperature, relative humidity, wind and 24–hour rainfall (Stocks, Lawson *et al*., 1989; de Groot, Wardati *et al*., 2005). In the United States, fuel moisture was utilized for various fire rating systems: the National Fire Danger Rating System (NFDRS) of the USDA Forest Service utilized Fuel Moisture Stick to predict above–ground fuel moisture content, and evaluation of fine temporal–scale dynamics of fuel moisture to investigate their relationships with fire risk (Deeming, Burgan *et al*., 1977; Fosberg, 1977).

Studies have shown that under similar weather conditions, fuel moisture content can have a positive influence on the speed of fire spread, such as *Pinus resinosa* stands (Van Wagner, 1967; Van Wagner, 1975). In particular, fire risk due to aboveground woody fuel increased with lower fuel moisture content, and that the fuel moisture content was largely influenced by the combination of fuel types (ratio of live and dead fuel, density, porosity, size), quantity of each fuel type, and weather conditions (precipitation, relative humidity, and temperature) (Fons, 1946; Brown, 1970; Viney and Catchpole, 1991; Xanthopoulos and Wakimoto, 1993).

Catchpole and others (2001) showed how fuel moisture content changed in response to temperature and humidity under various field conditions. De Groot and others (2005) investigated the dynamics of Fine Fuel Moisture Content and its relationship with ignition threshold for various grass species in Indonesia over 8 months. A research by Yamashita (1988) showed that the decrease

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in moisture level of fine fuel started from the surface, and the deeper layer showed moisture level drop after several hours, and that the rate of decrease was greater with higher solar irradiation and wind speed. It also indicated that in the event of precipitation, fuel moisture responded more sensitively in stands with lower canopy cover where it increased more quickly, while drying rate was dependent on the combination of solar irradiation, wind speed, air temperature, humidity, and fuel density.

Moisture content of forest fuel is an important factor for the ignition, burn intensity and spreading rate of forest fire. While it is generally known that lower fuel moisture can increase fire probability, a successful fire event requires a variety of conditions, such as a combination of low fuel moisture and climate and meteorological conditions that enables a valid ignition event and further spread to surrounding fuel.

In Korea, unfortunately, there are few studies on forest fire risk conditions based on fuel moisture level, and the dynamics of forest fuel moisture content in particular is not well known. Chae (2003) investigated the temporal change in moisture content of fine fuels for 27 native tree species in Korea, but the study was limited to laboratory conditions which is not sufficient to describe and evaluate the dynamic field conditions. Kwon (2009) evaluated fuel moisture level for pine stands in the Donghae and Samcheok region of Korea, which were later used in conjunction with meteorological data and fuel moisture level, a fine fuel moisture prediction model was developed (Lee, Kwon *et al*., 2010). However, both studies have limited scope in regards to site conditions, fuel types, and stand characteristics considered.

In this study, we studied the dynamics in fine fuel moisture in a deciduous forest stand in the Yeongdong region of Korea. We measured fuel moisture level changes for specific fuel size classes over 6 days after a significant precipitation event (>5 mm in 24 hours) in the spring of 2008, which were then used to develop a predictive fuel moisture model. We limited our study to spring season when fire risk is highest throughout the year.

MATERIALS AND METHODS

1. Study area and survey

The study was conducted at three sites in a deciduous forest stand located in Samcheok region of Korea (Table 1). The sites were selected so that a variety of tree canopy cover levels could be represented, similar to the sampling scheme used by Tanskanen (2005). During the spring months of 2008, fuel moisture of aboveground woody fuel was measured for 6 days at 10 am on a daily basis, starting from the day when cumulative precipitation exceeded 5.0 mm (total 4 events, Table 2). Precipitation threshold was based on a previous study in Korea indicating that most fuel remained dry enough if precipitation was less than 5.0 mm (Kang, Kim *et al*. 2002). We randomly located a study plot (10×10 m) within each site, from which aboveground fuel samples were collected from 3 micro plots (0.2×0.2 m). Fuel samples were classified into 4 different diameter size classes (<0.6 cm, 0.6–3.0 cm, 3.0–6.0 cm, and >6.0 cm), which were weighed on site and then sealed into plastic bags and transported to the laboratory for further measure-

Table 1. Stand Investigation and Site Investigation in the Survey Site

Item / Stand	Stand investigation					Site investigation					Fallen leaves and humus layer thickness(cm)		
	Species	Average Height (m)	Average DBH (cm)	Degree of closure (%)	Trees (ha)	Altitude (m)	Direc –tion	Survey location	Average slope (°)	GPS	Fallen leaves layer	Humus layer	Total
Loose	*Quercus dentata*	1.7	5.3	20	500	27	S20E	bottom	13°	N 37° 26' 08.9" E 129° 05' 31.7"	1.0	1.8	2.8
Medium	*Quercus variabilis*	6.7	11.3	60	1700	38	S30E	bottom	11°	N 37° 25' 26.0" E 129° 06' 32.3"	2.1	2.8	4.9
Dense	*Quercus variabilis*	7.2	12.2	70	2000	40	S20W	bottom	9°	N 37° 25' 25.2" E 129° 06' 27.7"	2.2	3.0	5.2

Table 2. Survey Period of Fuel Moisture

Item / Investigation	Duration of rainfall	Survey period	Accumulation rainfall
First investigation	'08 March 22~24	'08 March 25~March 29	44.0 mm
Second investigation	'08 March 30	'08 March 31~April 5	10.0 mm
Third investigation	'08 April 17	'08 April 18~April 23	5.5 mm
Fourth investigation	'08 May 12~13	'08 May 14~May 19	25.6mm

ment and analyses. Various meteorological measurements were made at the time of fuel sample collection: temperature, relative humidity, wind speed (Kestrel 4000, Nielsen–Kellerman), and solar irradiation (INS DX–200).

2. Analysis

2.1 Fuel sample analysis

Once transported to the laboratory, the sampled fuel was desiccated in a dry oven for 24 hours at 105˚C and weighed again to estimate fuel moisture content (FMC) estimate (Anderson, Schuette *et al.*, 1978). We then analyzed fuel moisture by 4 different fuel size classes and the canopy cover of the stand from the following formula:

$$FMC\ (\%) = \left(\frac{W_w - W_d}{W_d}\right) \times 100 \quad \text{................equation 1}$$

where *FMC* is the Fuel Moisture Content in percentage, W_w is wet weight, and W_d is dry weight.

2.2 Development and validation of fuel moisture prediction model

We built fuel moisture regression models for each of the fuel size class by using the fuel moisture content (FMC) as a function of relative humidity, cumulative solar irradiance, canopy cover class, and day–since–precipitation (SPSS version 16.0.2). Relative humidity was calculated as a weighted mean effective humidity based on the five humidity measurements taken during the five days from the first survey date, based on the following formula:

$$H_e = (1-r)(H_0 + rH_1 + r^2H_2 + r^3H_3 + r^4H_4) \quad \text{......equation 2}$$

where r is a fixed constant of 0.7, H_0 is the relative humidity at the time of the first survey date, and H_n is the relative humidity of the nth day after the first survey.

Both relative humidity and cumulative solar irradiance were log–transformed to obtain linearity. Wind speed was excluded from the analysis because its influence was negligible in the overall model performance based on preliminary analysis. Canopy cover was set as two sets of dummy variables to specify three of the cover classes considered.

The resulting models were validated against an independent dataset surveyed for 6 days starting from April 2 of 2009, after a precipitation event of 22.5 mm.

RESULTS AND DISCUSSION

1. Comparing fuel moisture changes

1.1 Comparison between fuel size

Fuel moisture of the smallest size class (<0.6 cm) in stands with high canopy cover was 4–11% higher compared to stands with medium canopy cover, and 7–16% higher than stands with low canopy cover.

The smallest fuel size class in stands with low canopy cover showed the fastest reduction in fuel moisture, as it only took 3 days since precipitation event to reach the fire risk moisture level of 17%, compared to 4–5 days required for those in the medium density stands (Fig. 1). The fuel moisture content (FMC) of the smallest size class showed continuous reduction even in stands with high canopy cover, suggesting that it could quickly reach a level close to fire risk level. However, the reduction rate clearly slowed down towards the end of the survey period (Fig. 1). The fuel size class of 0.6–3.0 cm showed rapid reduction in fuel moisture for the first 1–3 days, and fuels under low canopy cover reached fire risk level on day 5, and that under medium canopy cover reached fire risk level on day 6 (Fig. 2). These results were comparable with a previous study on moisture condition of fallen leaves and fire risk in Japan (Technical Committee on Forest Fire 1984).

Fuel with size class 3.0 to 6.0 cm showed 70–100% moisture level on the next day since precipitation, and the drying rate did not slow down after day 6, sustaining its rate of moisture reduction. On the last day of survey, fuel moisture content (FMC) of this size class was higher than 30% in canopy cover levels, indicating that relatively low risk of fire was maintained. With the continuing rate of fuel moisture reduction, it is likely that fuel moisture level may only reach fire risk level as late as 7 to 8 days post precipitation event (Fig. 3).

The largest fuel size class (>6.0 cm) showed very

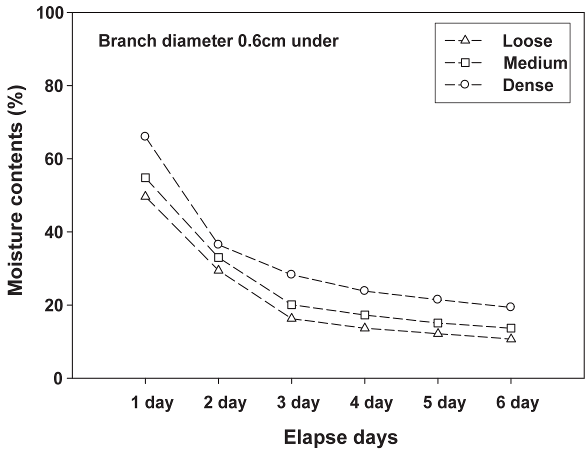

Fig. 1. Fuel Moisture Content Change of 0.6 cm under.

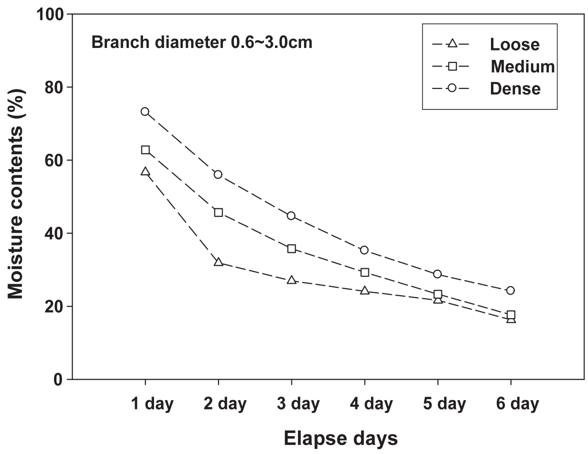

Fig. 2. Fuel Moisture Content Change of 0.6~3.0 cm.

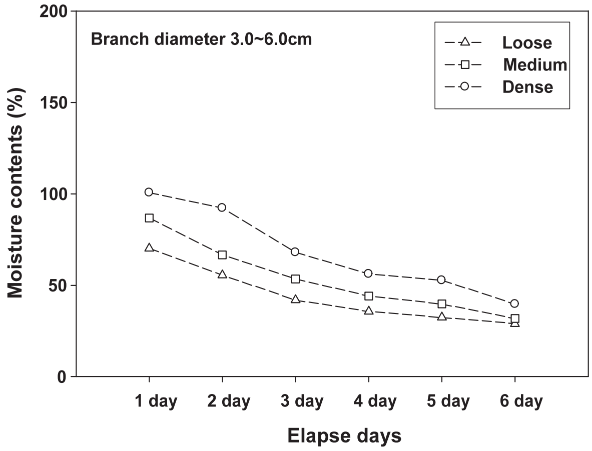

Fig. 3. Fuel Moisture Content Change of 3.0~6.0 cm.

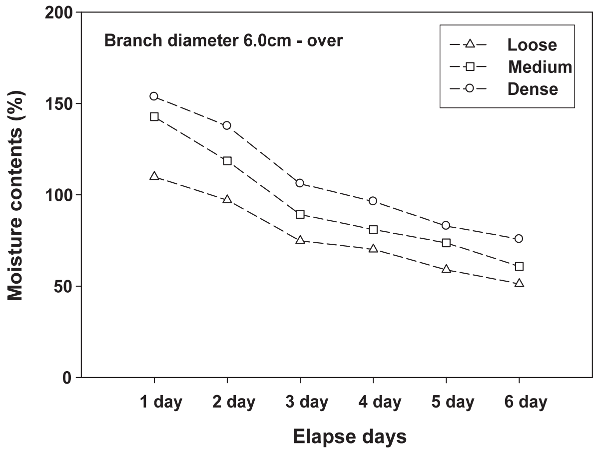

Fig. 4. Fuel Moisture Content Change of 6.0 cm over.

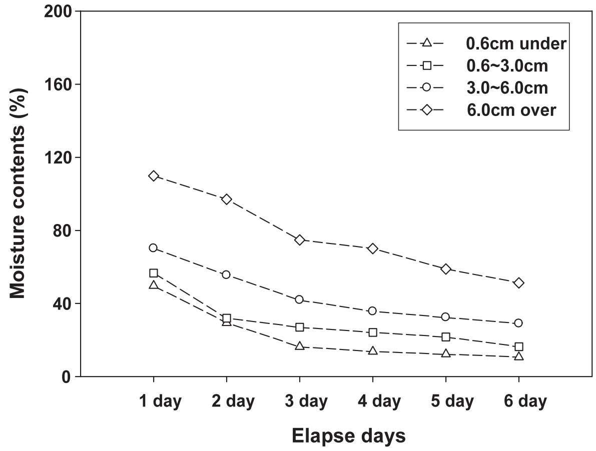

Fig. 5. Fuel Moisture Content Change of Loose Stand.

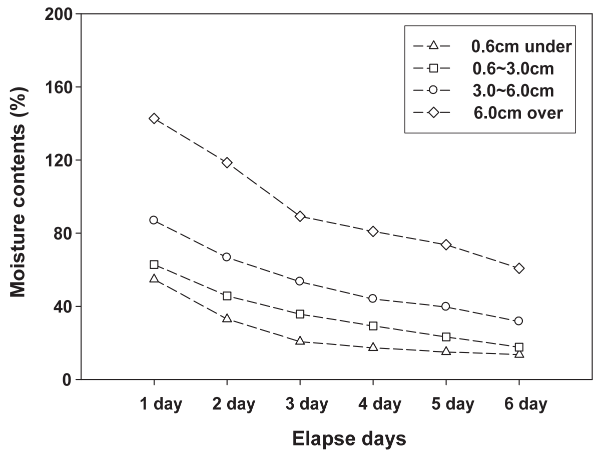

Fig. 6. Fuel Moisture Content Change of Medium Stand.

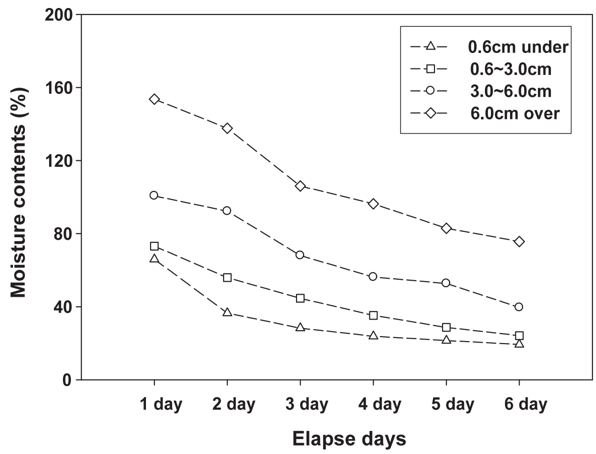

Fig. 7. Fuel Moisture Content Change of Dense Stand.

high moisture content (100–150%) on the next day of precipitation, which was sustained throughout the survey period (Fig. 4). Moisture level stayed at the range of 51–75% even on day 6, which indicates low fire risk. Overall, fuels greater than 3.0 cm size class showed limited fire risk even after day 6, and smaller fuels had a steep rate of moisture reduction and reached fire risk level shortly after the precipitation (Kwon and Lee *et al.*, 2011).

1.2 Comparison between canopy cover class

Fuel in dense stands had higher fuel moisture level throughout the survey period (Fig. 5, 6 and 7). In addition, the rate of fuel moisture reduction was influenced by canopy cover class. In particular, the difference in fuel moisture reduction rate was more evident for the smallest size class. fuel moisture content (FMC) of smaller fuels (<3.0 cm) was lower than larger fuels (>3.0 cm) by 26–46%, 30–56%, and 35–69% for low, medium, and high canopy stands, respectively.

2. Fuel moisture prediction model

The correlation and regression analyses for fuel moisture of each of the fuel size class showed significant results (Table 3, 4). In particular, fuel moisture content (FMC) of smaller fuel sizes (<6.0 cm) showed high correlation with cumulative solar irradiation, effective humidity,

Table 3. Correlations Analysis between Fuel Moisture Content and Factor

0.6 cm under		0.6~3.0 cm		3.0~6.0 cm		6.0 cm	
Pearson Correlation	FMC	Pearson Correlation	FMC	Pearson Correlation	FMC	Pearson Correlation	FMC
log10 (AI)	–.781	log10 (AI)	–.796	log10 (AI)	–.786	log10 (AI)	–.814
log10(EH)	.643	log10 (EH)	.623	log10 (EH)	.581	log10 (EH)	.341
log10 (ED)	–.812	log10 (ED)	–.802	log10 (ED)	–.673	log10 (ED)	–.395
L	–.354	L	–.359	L	–.362	L	–.772
M	–.036	M	.015	M	.016	M	.246

* Remarks: FMC=fuel moisture content (%), log10 (EH)=effective humidity (%), log10 (AI)=accumulation irradiation (lux), log10 (ED)=elapse day (day), L=loose, M=medium

Table4. Fuel Moisture Prediction Model Expression by Statistics Analysis

0.6 cm under	FMC=1.780+0.009*Log10(EH)-0.062*Log10(AI)-0.176*(L)-0.019*(M)-0.599*Log10(ED)	(R^2=0.927)
0.6~3.0 cm	FMC=2.169-0.079*Log10(EH)-0.173*Log10(AI)-0.07*(L)-0.065*(M)-0.499*Log10ED)	(R^2=0.870)
3.0~6.0 cm	FMC=2.357+0.056*Log10(EH)-0.343*Log10(AI)+0.0463*(L)-0.054*(M)-0.223*Log10ED)	(R^2=0.795)
6.0 cm over	FMC=1.904-0.091*Log10(EH)-0.164*Log10(AI)-0.164*(L)-0.042*(M)-0.181*Log10(ED)	(R^2=0.847)

* Remarks: FMC=fuel moisture content (%), log10 (EH)=effective humidity (%), log10 (AI)=accumulation irradiation (lux), log10 (ED)=elapse day (day), L=loose, M=medium

and days since precipitation, but moderately so with canopy cover class (Table 3). Regression analysis resulted in significant models ($P<0.05$) for all fuel sizes considered, with good performances (R^2 ranging from 0.795 (fuel size 3.0–6.0 cm) to 0.927 (fuel size <0.6 cm) (Table 4).

3. Validation of the prediction model

The model performance was compared with an independent dataset (Fig. 8, 9, 10 and 11). The model underestimated fuel moisture level of the smallest and largest fuel size class, but overestimated for the mid–sized classes (0.6–6.0 cm), especially in the early days after precipitation. In particular, fuel moisture content (FMC) of the smallest fuel size class was underestimated in stands with high canopy cover, but were relatively consistent in stands with mid– and low canopy cover, especially from day 2 to 6 (Fig. 8). FMC of fuel size class 0.6–3.0 cm was

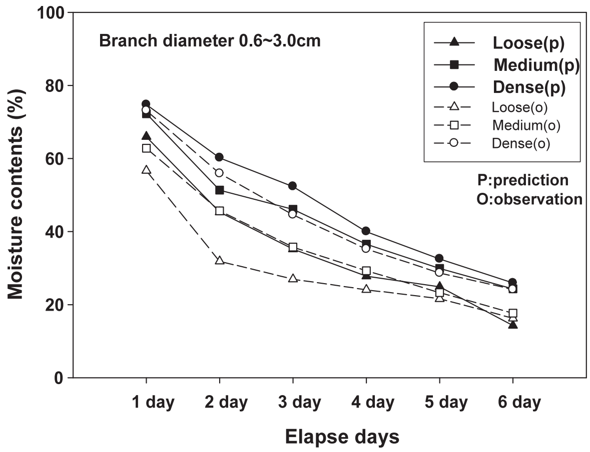

Fig. 9. Fuel Moisture Content Change of 0.6~3.0 cm.

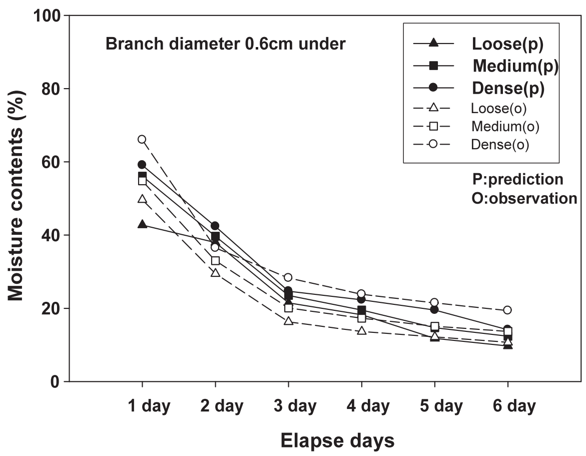

Fig. 8. Fuel Moisture Content Change of 0.6 cm under.

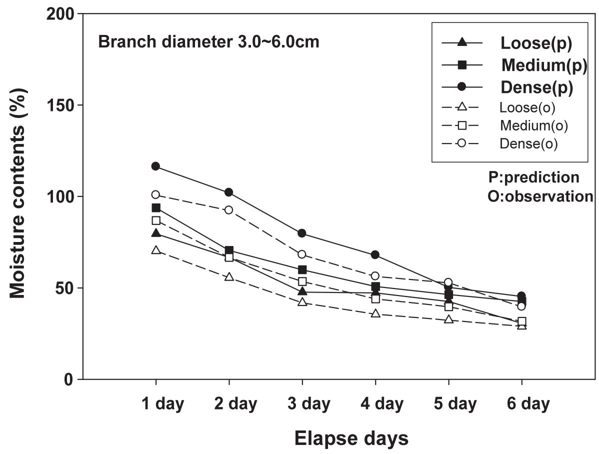

Fig. 10. Fuel Moisture Content Change of 3.0~6.0 cm.

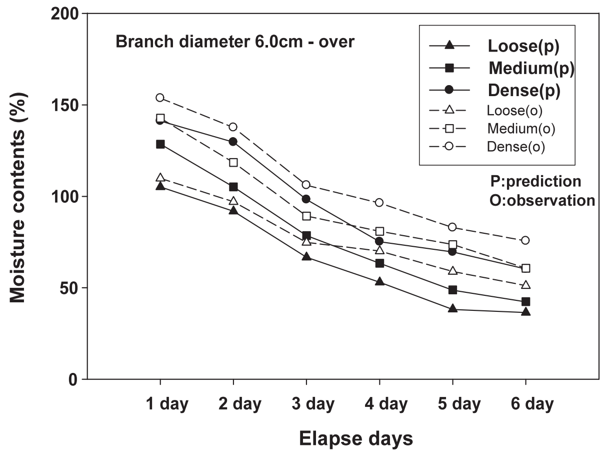

Fig. 11. Fuel Moisture Content Change of 6.0 cm over.

consistently overestimated for all canopy cover classes (Fig. 9). Fuel moisture content (FMC) of fuel size class 3.0–6.0 cm was also slightly overestimated for all canopy cover classes (Fig. 10). In contrast, fuel moisture content (FMC) of the largest fuel size class (>6.0 cm) was underestimated across all canopy cover classes (Fig. 11).

CONCLUSION

This study showed the fuel moisture dynamics of down woody fuel of various sizes after a significant precipitation event (>5 mm within 24 hours) in a deciduous forest stand in Yeongdong region of Kangwon province in Korea. Four different fuel size classes and stand density were identified to construct regression models, which were validated against an independent dataset. The conclusions of this research can be summarized as follows.

1) Woody fuel of the smallest size class (diameter <0.6 cm) showed the most rapid rate of fuel moisture reduction. Such effect was more prominent in stands with low canopy cover where fire risk moisture level of 17% was reached only after 3 days since precipitation, compared to 4–5 days for medium– and high density stands. Medium–sized fuel (0.6–3.0 cm) reached fire risk fuel moisture level after 5–6 days in a low density stand, but in a medium density stand it took 6 days.
2) Medium–large fuels (diameter 3.0–6.0 cm) sustained fuel moisture level greater than 30% even after 6 days from the precipitation event, suggesting that fire risk may remain low. Large fuels (diameter >6 cm) showed 51–75% of fuel moisture after 6 days, showing lowest fire risk among all fuel size classes.
3) The fuel moisture prediction models performed reasonably well when validated against an independent data set, and such results suggest that our models could be successfully utilized for developing a fire risk rating system for the region.

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