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A modified model of direct estimation method for fine fuel moisture content prediction by considering crown density

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Abstract

Moisture content of forest fine fuel is one of the most important factors for forest fire risk assessment and fire spread prediction. The weather parameters above the fuel surface used in Catchpole's existing Direct Estimation Model are not suitable for forecast. The crown density of the forest area in the model, which may has great influence to the fine fuel moisture content in the forest, is not considered. A series of outdoor experiments were carried out in order to study the effect of the crown density, including 3 simulated crown densities and 2 real tests. In the experiments, the collected Pinus Sylvestris needles in the Da Hinggan Mountains of China are used. The dynamic variations of the weights of the needles are captured in 0.5 h or 1 h interval, and the dry weights of them are measured after 24 h kiln dry. During the experiments, the local meteorological data including the temperature, the humidity and the winds velocity, are recorded from the homepage of Weather China at the same time. Based on the experiments, a modified model for fine fuel moisture content prediction is achieved, in which the crown density is used to adjust the temperature and the humidity near the fuel surface. The comparison results show that under different conditions of crown densities, the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE) of the modified model are decreased significantly, and the Mean Absolute Percentage Errors (MAPE) for different crown densities are all less than 6%. The contrast validation between forest field observation and the prediction values of the modified method indicates that the absolute errors are less than 10%. This modified method can effectively reduce the prediction errors due to different crown densities; meanwhile, the calculation is using meteorological forecast data directly, so it has better applicability.

Nomenclature

t_i	time
Δt	the interval between t_i and t_{i-1}
m_i	the actual moisture content
m_{i-1}	the moisture content at t_{i-1} (the actual value at the beginning or the prediction value the last moment)
$\hat{m}_i$	the prediction moisture content calculated by Eq.(1)
$m(t_i)$	the prediction value of moisture content at t_i,
q	the equilibrium moisture content
q_i	the equilibrium moisture content at t_i
q_{i-1}	the equilibrium moisture content at t_{i-1}
T_f	the temperature above fuel surface (°C)
T_a	atmosphere temperature at the meteorological station (°C)
H_f	the relative humidity above fuel surface (%)

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H_a	the relative humidity at the meteorological station (%)
R	universal gas constant (8.314 J·K^{-1}·mol^{-1})
M	the relative molecular mass of H_2O (18 g·mol^{-1})
a, b	undetermined coefficient
SSE	the Error Sum Squares, $SSE = \sum_{i=1}^{n}(m_i - m_i)^2$
I	the solar radiation intensity without shelter (W/m^2)
D	crown density (%)
u_f	wind speed above fuel surface (m/s)
u_{bole}	the wind speed at tree bole (m/s)
u_{tree}	the wind speed on the top of the tree (m/s)
u_s	the average wind speed at the height of 10m above earth at meteorological station (m/s)
H_{bole}	the height of the bole (m)
H_{tree}	the tree height (m)
d	the zero horizontal displacement (m)
z_0	the length of roughness (m)
MAE	the Mean Absolute Error
$RMSE$	the Root Mean Square Error
$MAPE$	the Mean Absolute Percentage Error
AE_{Max}	the Maximum Absolute Error
APE_{Max}	the Maximum Absolute Percentage Error

Greek symbols

α	canopy leak coefficient relevant to crown density (dimensionless)
λ	$\exp(-\Delta t/(2\tau))$
τ	the time-lag of fuel

Subscripts

i	the measurement point measured every half hour from 8:30 to 17:00
f	fuel surface
a	atmosphere

1. Introduction

Moisture content of forest fine fuel, one of the most important factors influencing the reaction of forest fires [1], directly affects the possibility for catching on fire. It's critical that the variation of moisture content of forest fine fuel be predicted accurately when forecasting the fire danger of forest and fire behavior [2, 3].

So far, there are four ways to predict the moisture content of fine fuel: equilibrium moisture content [4, 5], method of regression with meteorological element [6, 7], estimating by remote sensing [7] and process modeling [8]. Equilibrium moisture content method is the most widely used model and of the highest accuracy which unavoidably has the highest requirements for calculate parameters [9]. Due to equilibrium moisture content model by Nelson [10], moisture content of fine fuel depends on the environment around the fuel surface if there is no precipitation. The dynamic moisture content always lags behind the environment change because the ambient temperature and humidity are impacted by many factors. Catchpole analyzed the outdoor experimental data by nonlinear regression method and established a direct dynamic moisture content estimate method based on Nelson's equilibrium moisture content model [4]. After constantly observing the moisture content variation of larch dead branches with different diameters with varying ambient temperature and humidity and analyzing the effectiveness of Catchpole's direct estimation method, Kingson found out that the prediction error is small when the modeling sample number is comparatively large (about 84) [11]. The temperature and humidity data used in Catchpole's method is collected through actual measurement from the fuel surface in forest. The forecast data in the future is the only available data when predicting forest fire danger. The accurate forecast data in forest is hard to attain when predicting the fire spread behavior. Under these conditions, the effectiveness of Catchpole's method needs to be validated. When using meteorological forecast data, the meteorological parameters in forest need to be corrected. Forests with different crown density have different solar radiation and wind speed at fuel surface which greatly impacts the moisture content. It is necessary to modify the moisture content considering the crown density.

This paper simulates different crown density conditions in lab small-size experiments, observes the constant variation of mass change of Pinus Sylvestris needle and calculates the moisture content. At the same time, it records meteorological data

like ambient temperature, humidity and wind speed released by China's meteorological nets and introduces crown density to modify Catchpole's direct estimation method. Firstly, validate the effectiveness of the modified model by cross validation. Secondly, compare the indexes like mean absolute error (MAE), root mean square error (RMSE) and mean absolute percentage error (MAPE) between the predicted results and experiment results before and after the model modification and verify the rationality of modified model. Finally, choose two forests with different crown density as experiment places to verify the actual prediction accuracy of the model.

2. Experiment and data analysis methods

2.1. Measurement for moisture content of fuel under different crown density condition

Pinus Sylvestris needle used as experimental material were collected in Jiagedaqi and Huzhong Hongwei forests in Greater Khingan, May 2009. Pine needles were preprocessed before the experiments. Immerse the pine needles in water for 1 hour, then put them in the constant temperature and humidity chamber for 24 hours after draining off the surface water so that the pine needles reach the equilibrium moisture content.

Firstly, a series of simulation experiments are carried out to repetitively control the crown density variation well. Three samples of pine needles all weighed 100 g. They were evenly laid on plastic crate with a size of 40 cm×60 cm and laid for 2.5 cm thick. Sunshade nets with shading rate of 0.3, 0.6, 1.0 respectively were used to simulate different crown density. The plastic crates were put outside where they could be directly exposed to the sun. The needles' weight was recorded every half an hour from 8:30 to 17:00. The meteorological data like temperature, humidity and wind speed from the China's weather net were recorded accordingly. At last, the needles were put in the dryer with a temperature of 378 K to dry for 24 h. Moisture content at each moment was calculated after the needles' gross weight was weighed. Each experiment was carried out for three times marked T_1, T_2, T_3. Total 162 samples were collected for the modeling.

Secondly, two forests with different crown density were chosen to carry out the testify experiments. The fuel materials were prepared as prepared in the first series. The same samples of pine needles were exposed without any shelter on the forest ground. Due to the limited experiment condition, the needles were weighted for every hour and the meteorological data were recorded accordingly. The method by Qi et al. [12] was used to measure the crown density. This crown canopy density measurement method was based on fisheye lens. A mean value was calculated after 3 measurements in each forest. The needles were brought back to the laboratory to weigh the gross weight and calculate the moisture content.

2.2. Data analysis methods

2.2.1. Direct estimation methods by Cathpole et al. [4]

Catchpole et al. [4] assumed equilibrium moisture content remain constantly as q_i between $t_i - \Delta t/2$ and $t_i + \Delta t/2$. By solving the differential equation of fine fuel dehydration and water absorption process in time interval between t_i-1 and t_i, moisture content at t_i was obtained as shown in Eq. 1:

$$m(t_i) = \lambda^2 m_{i-1} + \lambda(1-\lambda)q_{i-1} + (1-\lambda)q_i \qquad (1)$$

where $m(t_i)$ is the predicted value of moisture content at t_i, m_{i-1} is the moisture content at t_{i-1} the actual value at the beginning or the predict value the last moment, Δt is the interval between t_i and t_{i-1}, q_{i-1} is the equilibrium moisture content at t_{i-1}, q_i is the equilibrium moisture content at t_i, $\lambda = \exp(-\Delta t/(2\tau))$ and τ is the time-lag of fuel.

Equilibrium moisture content q in Eq. 1 can be calculated by Nelson's model [10]:

$$q = a + b \log\{-\frac{RT}{M} \log H\} \qquad (2)$$

where T is the temperature at fuel surface (K), H is the relative humidity at fuel surface (%), R is universal gas constant (8.314 J·K⁻¹·mol⁻¹), M is the relative molecular mass of H_2O (18 g·mol⁻¹), a and b are undetermined coefficient.

Undetermined coefficient a, b and time-lag τ are relevant to fuel type and could finally be determined by fitting several sample data. Where m_i is the actual moisture while $\tilde{m}_i$ is the prediction moisture content calculated by Eq. 1. Square error

and $SSE = \sum_{i=1}^{n}(m_i - \hat{m}_i)^2$ are the objective functions. Nonlinear estimation is carried out with the constraint condition-the minimum objective function value, then a, b and time-lag τ are determined. Kingson thought better fitting results would be obtained when there were comparatively large modeling samples (84 samples) [10].

2.2.2 .Corrected model considering crown density

Temperature and humidity data used in Catchpole's direct estimation method are the actual measurement values in forest. In the actual application process, observation data obtained outside the forest or the data from the weather report are needed to predict moisture content. Therefore, this paper established the model using meteorological observation data to improve the applicability of the model. It is found out that different crown densities due to different solar radiation caught by fuel on earth impacts the moisture content. Crown density factors are introduced to modify the direct estimation method.

The modification of fuel surface temperature and humidity referred to Byram & Jemison's [13] method. Modification factors were introduced to this method:

$$T_f = T_a + \frac{(1-D)I}{42.5u_f + 32.7} \tag{3}$$

where T_f is the temperature of fuel surface (°C), T_a is atmosphere temperature at the meteorological station (°C), I is the solar radiation intensity without shelter (W/m^2), D is crown density, u_f is wind speed at fuel surface (m/s). The calculation of is discussed in the following part.

$$H_f = H_a \exp(-0.059(T_f - T_a)) \tag{4}$$

where H_f is the relative humidity at fuel surface (%), H_a is the relative humidity at the meteorological station (%).

According Zhu [14] on wind speed profile variation rule, wind speed profile above the forest obeyed logarithmic distribution, wind speed profile at the crown obeyed index distribution and wind speed profile at the forest stand was indicated by wind attenuation coefficient. Therefore the wind speed at fuel surface is calculated by Eqs. 5 and 6:

$$u_f \approx u_{bole} = u_{tree} \exp\left[-\alpha(1 - \frac{H_{bole}}{H_{tree}})\right] \tag{5}$$

where u_{bole} is the wind speed at tree bole (m/s), u_{tree} is the wind speed on the top of the tree (m/s), α is canopy leak coefficient relevant to crown density(dimensionless), H_{bole} is the height of the bole (m), H_{tree} is the height of the top of the crown (m).

$$u_{tree} = u_s \frac{\ln\left((H_{tree} - d)/z_0\right)}{\ln\left((10 - d)/z_0\right)} \tag{6}$$

where u_s is the average wind speed of 10m above earth at meteorological station (m/s), d is the zero horizontal displacement (m), z_0 is the length of roughness (m). For forest, d is 0.7 times of tree height and z_0 is 0.75 m [15].

The modified undetermined parameters a, b and time lag τ are determined by nonlinear regression analysis after modification.

3. Results and analysis

3.1. Cross validation of modified model

Both effectiveness and evaluation method are conducted to verify the validation of these experiments.

Effectiveness validation method for modified model: validate the model with cross validation method. Any two sets of data (108 samples) in T_1, T_2, T_3 are used as modeling data sets. The last set of data (54 samples) is used as validation data set. The modeling data sets are used to determine a, b and τ, so the validation data set can be predicted. Then *MAE*, *MAE* and

MAPE of predict results and actual results are analyzed to judge the effectiveness of model. Each cross validation experiment is carried out three times.

Evaluation method for modified model: All of the 162 sample data is fitted using Catchpole direct estimation method and modified model. Then such indexes like *MAE*, *RMSE* 和 *MAPE* are chosen to compare the accuracy of predict results before and after modification. Finally, validation experimental data in actual forest environment are used for comparison.

Error statistical results of the three validation experiments using cross validation method are shown in Fig. 1. MAE and RMSE remain the same in all the three validation experiments. Predict *MAPE* under three different crown densities is below 6.0%. Consequently, it is assumed that the modified model itself is stable and reliable.

Table 1. Statistics of the errors for cross-validation

No.	Dataset	D=0.3			D=0.6			D=1.0		
		MAE	RMSE	MAPE	MAE	RMSE	MAPE	MAE	RMSE	MAPE
1	Fitting T_1+ T_2	0.6	0.7	3.6%	0.6	0.6	3.4%	0.7	0.8	3.2%
	Validation T_3	0.4	0.5	3.1%	0.7	0.9	4.4%	0.9	0.9	4.7%
2	Fitting T_1+ T_3	0.5	0.6	2.7%	0.6	0.7	3.5%	0.7	0.8	3.3%
	Validation T_2	0.6	0.7	4.8%	0.5	0.6	3.3%	1.0	1.1	5.4%
3	Fitting T_2+ T_3	0.7	0.8	5.2%	0.4	0.5	2.4%	0.6	0.6	3.0%
	Validation T_1	1.1	1.1	5.9%	1.0	1.0	5.6%	0.3	0.4	1.5%

3.2. Comparative analysis and discuss before and after the modification

If the influence of the crown density is not taken into consideration, *a*, *b* and *τ* is determined by fitting the 162 sample data with nonlinear regression analysis using Eq. 2. Then *a* is 0.32, *b* is –0.108 and *τ* is 2.2. Therefore, the equilibrium moisture content equation is as follows:

$$q = 0.32 - 0.108 \log\{-\frac{RT}{M}\log H\} \tag{7}$$

If the influence of the crown density is taken into consideration, *a* is 0.39, *b* is –0.138 and *τ* is 2.2 after fitting the 162 sample data. Therefore, the equilibrium moisture content equation is as follows:

$$q = 0.39 - 0.138 \log\{-\frac{RT_f}{M}\log H_f\} \tag{8}$$

The actual moisture content of pine needle in 8:30 am is used as initial moisture content, time step is 0.5 h. Predict value of pine needle moisture content at each moment is calculated by solving Eq. 1 with Eqs. 7 and 8 and time-lag *τ*. Fig. 1 shows of dynamic variation of pine needles moisture content of group T_1, including three group of actual value and two predict value using two prediction methods. According to actual results (solid point) under different crown density, the lower is the crown density, the stronger the solar radiation is absorbed and the quicker the dehydration process is, the smaller the moisture content is. Catchpole direct estimation method didn't consider the influence of crown density and there was only a predict results (dash line and hollow diamond) with a high error. Having modified Catchpole's method, this paper gave accordingly predict results (solid line) under each crown density and predict results from this paper is more reasonable.
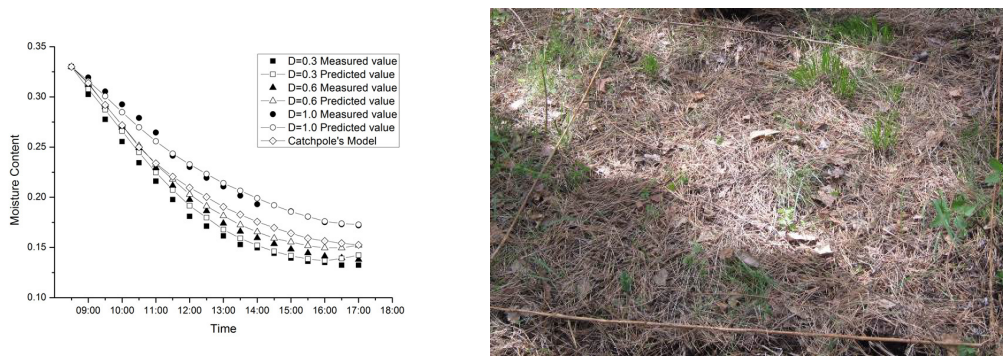
Fig. 1. Dynamic variation of pine needles moisture content and photo of sample.

The comparison of absolute error distribution between the Catchpole method and the modified model under three different crown densities is shown in Fig. 2. T_1, T_2, T_3 are the predict results of unmodified model. T_1^*, T_2^*, T_3^* are the results of modified model. The error of modified model is obviously less than that of unmodified model if crown density is lower (D=0.3) or crown density is higher (D=1.0).
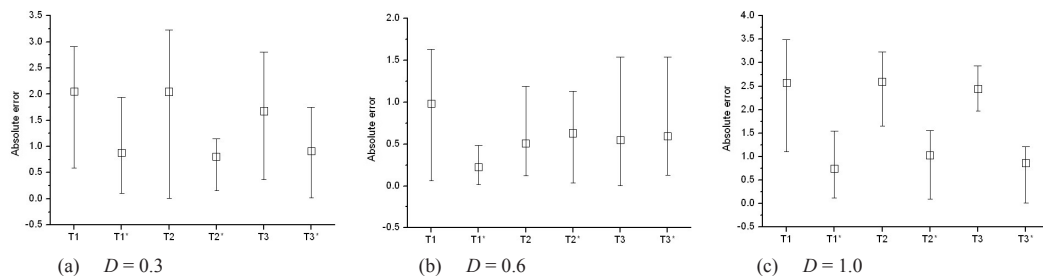

Fig. 2. Comparison of the Absolute Error Distributions between the Catchpole method and the modified model (marked with asterisk).

Statistical data of *MAE*, *RMSE* and *MAPE* of predict model of all condition is shown in Table 2. *MAE* and *RMSE* are comparatively low under the medium crown density condition (D=0.6) and *MAPE* is less than 10% at this situation. Under high (D=0.3) and low (D=1.0) crown density conditions, *MAPE* is more than 10%. After the crown density modification, *MAE* and *RMSE* are obviously reduced under all conditions. The maximum value of *MAPE* is 5.4%, that is to say, the accuracy of prediction is enhanced more than doubled. So the accuracy of prediction is higher after modification.

Table 2. Comparisons of Mean Absolute Error, Root Mean Square Error, and Mean Absolute Percentage Error between the Catchpole model and the modified model

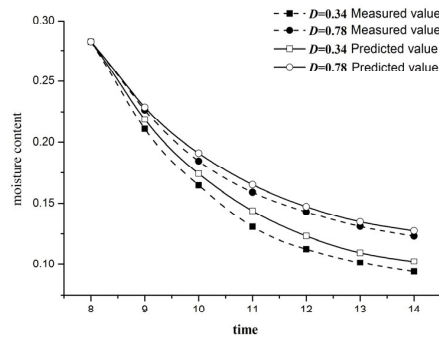|	Groups	D=0.3			D=0.6			D=1.0		
		MAE	*RMSE*	*MAPE*	*MAE*	*RMSE*	*MAPE*	*MAE*	*RMSE*	*MAPE*
T_1	Catchpole Model	2.1	2.2	12.7%	1.0	1.1	6.0%	2.6	2.6	11.6%
	Modified Model	0.6	0.7	3.2%	0.5	0.6	3.1%	0.5	0.6	1.9%
T_2	Catchpole Model	2.0	2.4	16.7%	0.5	0.6	2.7%	2.6	2.7	13.4%
	Modified Model	0.6	1.7	4.8%	0.5	0.6	3.3%	1.0	1.1	5.4%
T_3	Catchpole Model	1.7	1.9	12.5%	0.6	0.7	3.5%	2.4	2.5	13.0%
	Modified Model	0.9	0.9	4.7%	0.3	0.4	2.3%	0.6	0.8	3.9%

3.3. Results analysis

Fig. 3. Dynamic variation of pine needles moisture content in real forest environment.

Actual value and modified prediction value of pine needle moisture content in forests with respective crown density 0.34 and 0.78 are shown in Fig. 3. Pine needle moisture contents measured in the two forests are 12.3% and 9.4% respectively at 2:00, and they are differed by 3.9%. It's irrational to use Catchpole direct estimation method due to the only one predicted value. *MAE*, *RMSE* and *MAPE* of pine needle moisture content prediction in two forests are shown in table3. All the statistical errors with crown density of 0.34 are a little larger than those with crown density of 0.78. The lower crown density causes unstable solar radiation at fuel surface, unstable wind speed and unstable fuel surface temperature and humidity. These situations eventually enlarge predicted error. All statistical predicted errors of pine needle moisture content in both forests are lower after modification. The maximum absolute percentage error is under 10%. So the method in this paper can reduce moisture predicted error caused by different crown density and be well applied to forest district.

Table 3. The Maximum Absolute Error, Mean Absolute Error, Root Mean Square Error, Maximum Absolute Percentage Error and Mean Absolute Percentage Error of pine needles moisture content prediction in two forests.

D	AE_{Max}	MAE	$RMSE$	APE_{Max}	$MAPE$
0.34	1.3	1.0	1.0	9.9%	7.6%
0.78	0.6	0.5	0.5	3.9%	3.0%

4. Conclusions

This paper has carried out experimental research on the dynamic variation of moisture content of pine needle in the wild under different crown density condition. Then it proposes a prediction method for moisture content modifying Catchpole's direct estimation method considering the influence of crown density. The results show: Catchpole's method can only give one prediction value for moisture content change of fuel with different crown density. The predictive effect is better with a medium crown density. Under low or high crown density conditions, the prediction error is comparatively large and the mean absolute percentage error can be as high as 16%. After modifying, the model can give different prediction values for moisture content of fine fuel with different crown density and the mean absolute percentage error of the prediction results is under 6%. Results of demonstration tests in two forests with different crown density show the modified models have lower prediction error. Meanwhile, this modification method uses data from local meteorological station directly, which assures the prediction accuracy as well as broadens the applicability of the prediction model.

Acknowledgements

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