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Modelling sorption processes of 10-hour dead Pinus pinaster branches

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Abstract

Forest fuel moisture content is an important parameter that determines fire risk and fire behaviour. An accurate prediction of moisture content is therefore of great importance in fire management. In the fire risk period, dead forest fuel moisture content changes mainly by water vapour sorption processes so its knowledge enables the development of predictive fire risk models.

In the present work, the adsorption and desorption processes and equilibrium moisture content of 10-hour dead Pinus pinaster branches (diameter between 0.6 cm and 2.5 cm) were described in order to develop a moisture content prediction model for this type of fuels.

Laboratorial tests were used to determine sorption curves, timelag and equilibrium moisture content for different sets of air temperature (range between 20°C and 40°C) and relative humidity (range between 10% and 90%). The sorption curves and equilibrium moisture were also modelled with forest fuels and agricultural and food products existing models.

Field tests were used to evaluate the sorption and equilibrium moisture content models performance. Dead Pinus pinaster branches were collected in central Portugal through the year 2020 and 2021 on the Portuguese fire risk period (15th May to 15th October) between 12:00h and 13:00h LST. Samples with 0.6 cm to 2.5 cm diameter were collected and transported to laboratory to determine moisture content.

The laboratorial drying and wetting curves of dead Pinus pinaster branches (0.6 cm to 2.5 cm diameter) show that they are not pure exponential functions, but with different timelag values until equilibrium is reached. Additionally, the results suggest no significant relationship of the timelag periods with air relative humidity but a dependence with air temperature, showing an increase in the sorption rates with temperature. In terms of sorption curves, Modified Henderson and Pabis model provide the best fitting.

For this type of fuels, the representation of EMC values as a function of air relative humidity at constant temperature allowed to obtain a typical sigmoid curve. The EMC values obtained were higher for desorption process than for adsorption process, indicated the typical hysteresis effect in these processes. It was found that, besides the models used in forest fires, other EMC models are also suitable to predict fuel moisture content of dead Pinus pinaster branches, as the ones used in agricultural and food analysis.

1. Introduction

Forest fuel moisture content (FFMC) has a considerable influence on many aspects of forest fire behaviour, including rate of fire spread, ignition probability, flame dimensions and fuel consumption (Rothermel 1983; Viegas et al. 1992), however, its accurate prediction is difficult due to its interactions with weather conditions, topography and vegetation (Matthews 2014).

In the absence of rainfall, dead forest fuels respond to changes in meteorological conditions by sorption processes where it dominates water transfer mechanisms below the fiber saturation point. In these conditions, and at constant air temperature and relative humidity, the FFMC changes (increases or decreases) until it reaches a constant value designated equilibrium moisture content (EMC) (e.g. Catchpole et al. 2001; Viney and

Catchpole 1991). These moisture sorption processes are also characterized by a response time or log drying rate or timelag (τ) that is the time required for the fraction of evaporable water remaining in the forest fuel to decrease from 1 to 0.368 (Byram, 1963). Timelag is on the basis of forest fuels classification into four categories (1-hour, 10-hour, 100-hour and 1000-hour fuels) (Bradshaw et al. 1983).

In the present work, the adsorption and desorption processes and EMC of 10-hour dead *Pinus pinaster* branches (diameter between 0.6 cm and 2.5 cm) were determined in order to develop a moisture content prediction model for this type of fuels.

2. Methods

Laboratorial tests were used to determine sorption curves, timelag and EMC of dead *Pinus pinaster* branches (0.6 cm to 2.5 cm diameter) for different sets of air temperature (range between 20°C and 40°C) and relative humidity (range between 10% and 90%). Samples were placed inside a climatic chamber (Aralab Fitoclima 300) equipped with an analytical balance (precision of 0.001g). Continuous weighing was recorded until it reached constant weight, determining dead *Pinus pinaster* branches moisture content evolution and showing the changing rates at which equilibrium approaches.

In terms of mathematical modelling, sorption processes were modelled using the exponential equation described by Byram (1963) (equation 1), Page (1949) (equation 2), Henderson and Pabis (1961) (equation 3), two-term (Henderson 1974) (equation 4) and Modified Henderson and Pabis (Karathanos, 1999) (equation 5).

$$\mathrm{E(t)}_1 = \exp\left(\frac{-\mathrm{t}}{\tau}\right) = \exp(-\mathrm{k}_1\mathrm{t}) \tag{1}$$

$$\mathrm{E(t)}_2 = e^{-k_1 t^n} \tag{2}$$

$$\mathrm{E(t)}_3 = a_1 e^{-k_1 t} \tag{3}$$

$$\mathrm{E(t)}_4 = a_1 e^{(-k_1 t)} + a_2 e^{(-k_2 t)} \tag{4}$$

$$\mathrm{E(t)}_5 = a_1 e^{(-k_1 t)} + a_2 e^{(-k_2 t)} + a_3 e^{(-k_3 t)} \tag{5}$$

where τ is the timelag (h), t is time (h), k_1, k_2 and k_3 are the drying constants (h^{-1}) and n, a_1, a_2 and a_3 are empirical dimensionless constants. The fraction of evaporable water remaining in the fuel at time t, E(t), was calculated using equation 6. Model parameters and constants were obtained from laboratory data

$$\mathrm{E(t)} = \frac{\mathrm{m_{(t)}} - \mathrm{m_e}}{\mathrm{m_0} - \mathrm{m_e}} \tag{6}$$

where m(t) is the fuel average moisture content at time t, m_0 is the value of m at t = 0, m_e is the value of m as t approaches infinite (m_e approaches EMC).

To assess the relationship between EMC of dead *Pinus pinaster* branches and air temperature and relative humidity were used semi-empirical and empirical models such as Van Wagner (Van Wagner, 1987) (equation 7), Modified Halsey (Iglesias and Chirife 1976) (equation 8), Modified Oswin (Chen 1990) (equation 9), Nelson (Nelson, 1984) (equation 10) and Modified Chung-Pfost (Pfost et al. 1976) (equation 11).

$$EMC = \frac{1}{100}\left[a(100RH)^b + ce^{(100RH-100)/d} + e(21.1-T)(1-e^{100fRH})\right] \tag{7}$$

$$EMC = \left[\frac{e^{(a-bT)}}{-ln(RH)}\right]^{1/c} \tag{8}$$

$$EMC = (\mathrm{a} - \mathrm{bT})\left[\frac{RH}{(1-RH)}\right]^c \tag{9}$$

$$EMC = \frac{1}{a} ln\left(-\frac{RT_K}{Me^b} ln\left(\frac{RH}{100}\right)\right) \qquad (10)$$

$$EMC = -\frac{1}{a} ln\left[-\frac{(T+b)}{c} \ln{(RH)}\right] \qquad (11)$$

where a, b, c, d, e and f are coefficients specific to individual equations, RH is the relative humidity, T (°C) and T_k (K) are the temperatures, R is the universal gas constant (1.987 $cal.mol^{-1}K^{-1}$) and M is the molecular weight of water (18 $gmol^{-1}$). Model constants were obtained from laboratory data.

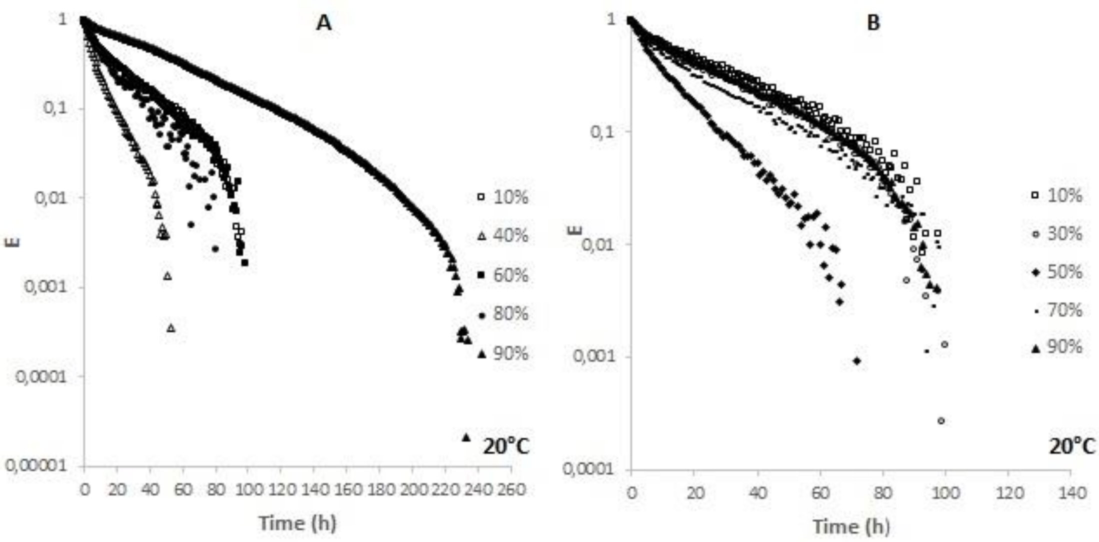
In the field tests, used to evaluate the sorption and EMC models performance, dead *Pinus pinaster* branches were collected from *Pinus pinaster* forest stands in Viseu (40°42'30.02"N, 7°54'8.96"W) in central Portugal through the year 2020 and 2021. Field sampling was performed on the Portuguese fire risk period (15th May to 15th October) between 12:00h and 13:00h LST. Samples with 0.6 cm to 2.5 cm diameter were collected and transported to laboratory in an isothermal bag to avoid moisture changes. Here, samples were weighted and then oven-dried at 105°C for 24 h, until constant weight, to obtain its dry weight and therefore the dry basis moisture content.

Hourly meteorological conditions (air temperature, relative humidity, wind and rainfall) from a weather station located approximately at 10 km south of the sampling site, were used to characterise weather conditions during field tests.

To assess the model fitting quality some statistical parameters were calculated namely the mean absolute error (MAE), the mean absolute percentage error (MAPE), the root mean squared error (RMSE) and the determination coefficient (R^2). RMSE and MAPE show the accuracy of model fitting, MAE measures the bias of the model and the R^2 measure how well observed values are replicated by the model. Usually, higher values of R^2 and lower values of MAE, MAPE and RMSE, associated with randomly distributed residuals indicate a good fit.

3. Results

Figure 1 shows the drying and wetting curves of dead *Pinus pinaster* branches represented by the evaporable water fraction (E), described in equation 6, as function of time for air temperatures of 20°C, 30°C and 40°C in a range of relative humidity between 10% and 90%. The drying and wetting curves show a deviation from pure exponential behaviour, which means that other functions should be considered as well to represent these processes. Additionally, these curves show some fluctuations, particularly in the late stages of the experiment mainly caused by temperature and relative humidity oscillations inside the climatic chamber.



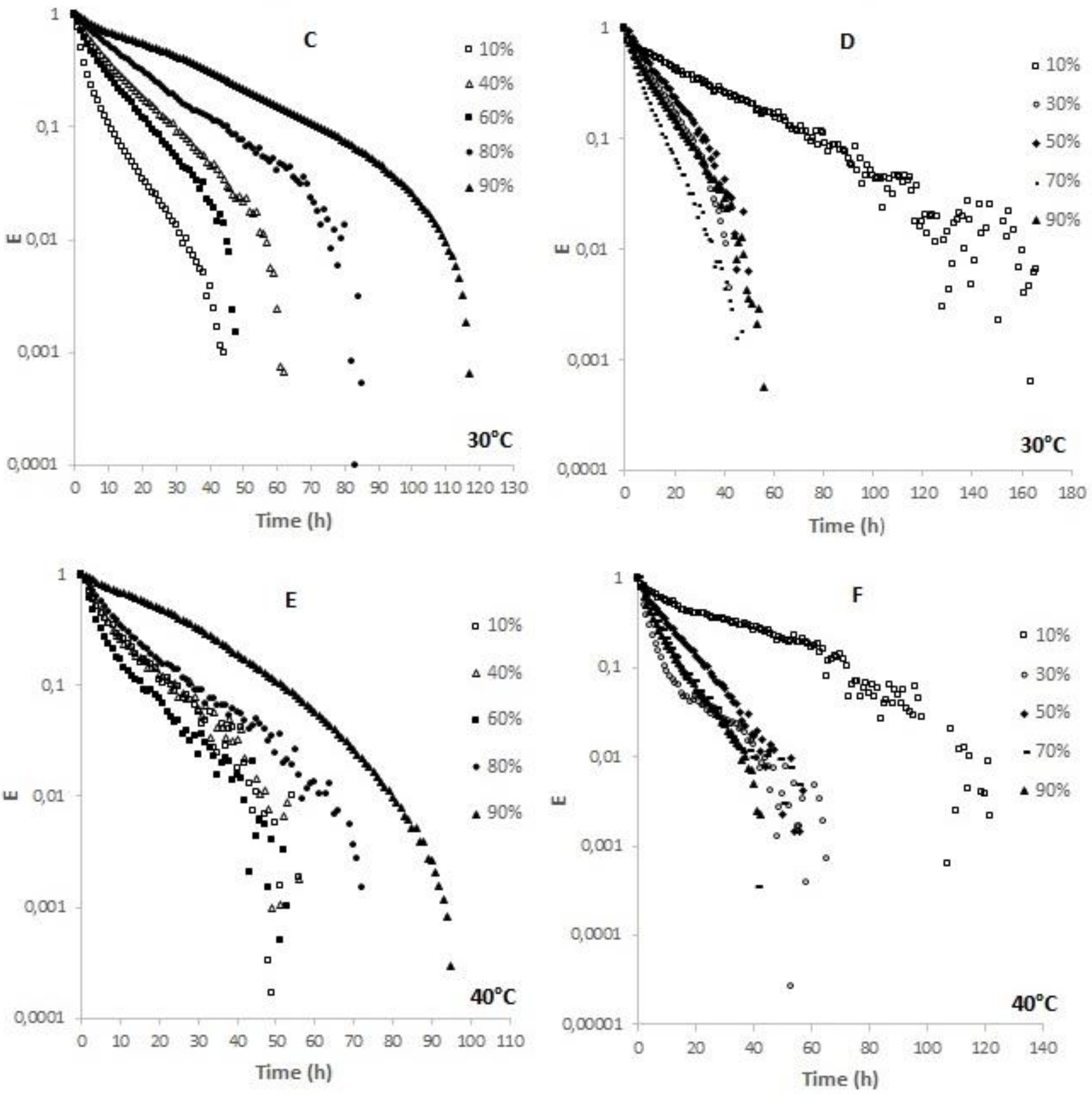


Figure 1- Semi-log graphs of desorption tests (A, C, E) and adsorption tests (B, D, F)

Breaking the drying and wetting curves in four periods and assuming a constant rate as fuel approaches EMC in each step, it was calculated the four timelag values. Table 1 shows the average timelag periods obtained in the laboratorial tests. No significant relationship of the four timelag periods with air relative humidity was found therefore an average value is presented. However, a dependence of the four timelag periods with air temperature was observed.

Table 1- Average timelag periods obtained in order of air temperature

Process	Temperature (°C)	First timelag (h)		Second timelag (h)		Third timelag (h)		Fourth timelag (h)	
		Average	s.d.	Average	s.d.	Average	s.d.	Average	s.d.
Desorption	20	20,99	14,04	26,46	11,38	19,89	11,50	16,76	6,09
	30	8,12	6,46	12,85	5,80	9,65	5,10	7,86	4,49
	40	8,23	6,43	9,96	4,24	9,60	4,02	7,37	2,62
Adsorption	20	19,02	7,60	23,32	8,25	22,38	9,98	13,71	10,48
	30	9,31	5,50	11,65	5,04	9,09	4,19	6,97	5,10
	40	6,29	3,40	12,09	11,29	8,89	4,44	6,65	3,20

Table 2 shows the estimated parameters for sorption processes based on the laboratorial tests for the models described from equation 1 to equation 5. As it can be seen, drying and wetting experimental curves are best fitted by the Modified Henderson with a R^2 of 0.694 and 0.749 and a RMSE of 0.134 and 0.116 for desorption and adsorption processes, respectively.

Table 2- Model parameters for the sorption processes

Equation			Byram	Page	Henderson and Pabis	Two-term	Modified Henderson and Pabis
Model parameters	K_1	Desorption	0.072	0.257	0.051	0.011	0.398
		Adsorption	0.073	0.269	0.047	0.014	0.171
	n	Desorption	-	0.533	-	-	-
		Adsorption	-	0.515	-	-	-
	a_1	Desorption	-	-	0.779	0.267	0.257
		Adsorption	-	-	0.753	0.323	0.622
	k_2	Desorption	-	-	-	0.160	0.106
		Adsorption	-	-	-	0.189	0.809
	a_2	Desorption	-	-	-	0.718	0.544
		Adsorption	-	-	-	0.666	0.071
	a_3	Desorption	-	-	-	-	0.007
		Adsorption	-	-	-	-	0.312
	k_3	Desorption	-	-	-	-	0.215
		Adsorption	-	-	-	-	0.014
Statistical parameters	R^2	Desorption	0.542	0.673	0.595	0.692	0.694
		Adsorption	0.565	0.730	0.636	0.748	0.749
	MAE	Desorption	0.129	0.107	0.124	0.104	0.103
		Adsorption	0.131	0.098	0.123	0.093	0.093
	RMSE	Desorption	0.163	0.138	0.154	0.137	0.134
		Adsorption	0.153	0.121	0.140	0.117	0.116

Laboratorial EMC values of *Pinus pinaster* branches obtained in both adsorption and desorption tests in a range of relative humidity between 10% and 90% for three air temperatures 20°C, 30°C and 40°C are shown in Table 3 and plotted in Figure 2. These results were fitted to five EMC models and Table 4 shows the EMC model parameter estimation obtained for the desorption and adsorption processes described in equation 7 to equation 11. As an example, the estimation by the Van Wagner model is also shown in Figure 2.

As can be seen, for a wide range of temperature and relative humidity values all sorption models show good fitting ability with the laboratory results however the Van Wagner model presented the best fit for both adsorption and desorption processes. This model gives the higher R^2 of 0.991 and 0.984, the lowest MAE of 0.428 and 0.453 and the lowest RMSE of 0.514 and 0.584 for desorption and adsorption processes, respectively. The residual distribution was also analysed and showed that all adsorption and desorption models presented a random residual distribution indicating good fitting ability and only Halsey model presented a systematic residual distribution.

The EMC values obtained were higher for the desorption process than for the adsorption process, presenting the typical hysteresis effect.

Table 3- EMC of dead Pinus pinaster branches for the tested air temperature and relative humidity conditions

Relative Humidity (%)	$EMC_{adsorption}$ (%)			$EMC_{desorption}$ (%)		
	T=20ºC	T=30ºC	T=40ºC	T=20ºC	T=30ºC	T=40ºC
10	2.1	2.3	1.8	5.7	5.5	4.5
20	3.7	2.7	3.7	7.5	6.9	6.4
30	5.0	4.1	4.7	9.0	8.3	7.8
40	8.6	6.9	5.7	11.2	10.0	9.4
50	10.9	7.9	7.1	11.7	1.1	10.5
60	11.1	9.8	8.9	13.7	12.9	12.6
70	13.1	12.4	11.3	-	-	-
80	14.5	12.9	13.8	16.8	17.0	15.9
90	18.0	17.6	17.0	23.0	24.0	21.1

Table 4- EMC model parameters estimation for the sorption processes

Equation			Van Wagner	Halsey	Oswin	Nelson	Chung-Pfost
Model parameters	a	Desorption	1.473	5.767	12.653	-0.183	0.183
		Adsorption	0.218	4.232	9.409	-0.193	0.193
	b	Desorption	0.531	0.012	0.053	5.236	57.182
		Adsorption	0.958	0.014	0.052	4.714	40.913
	c	Desorption	24.304	2.45	0.321	-	489.918
		Adsorption	68.193	2.07	0.390	-	236.158
	d	Desorption	8.442	-	-	-	-
		Adsorption	2.863	-	-	-	-
	e	Desorption	-389.814	-	-	-	-
		Adsorption	0.094	-	-	-	-
	f	Desorption	2.742×10^{-6}	-	-	-	-
		Adsorption	-0.042	-	-	-	-
Statistical parameters	R^2	Desorption	0.991	0.977	0.989	0.979	0.984
		Adsorption	0.984	0.903	0.944	0.968	0.977
	MAE	Desorption	0.428	0.702	0.384	0.579	0.421
		Adsorption	0.514	1.328	0.989	0.630	0.610
	RMSE	Desorption	0.514	0.818	0.563	0.776	0.681
		Adsorption	0.622	1.530	1.159	0.873	0.744
Residual distribution		Desorption	Random	Systematic	Random	Random	Random
		Adsorption	Random	Systematic	Random	Random	Random

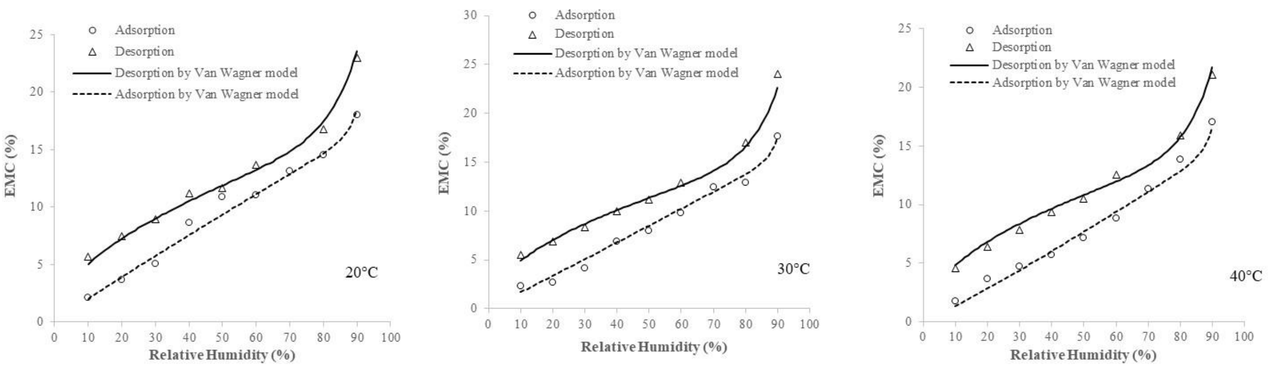


Figure 2- EMC of Pinus pinaster branches in both the adsorption and desorption processes. Estimates obtained by Van Wagner model.

In terms of model validation, Figure 3 shows the comparison between the predicted (line) and the observed (dots) FMC of *Pinus pinaster* branches. Predicted values result from the Modified Henderson and Pabis model for the drying and wetting curves and the Van Wagner model for EMC, both with empirical parameters estimated in the present work. The observed FMC values were obtained in the field tests. FMC values corresponding to rainfall events were excluded from the model validation.

Comparing the predicted and the observed FMC values, in terms of MAE, MAPE and RMSE, the results show a high prediction ability, with a MAE equal to 1.83%, a MAPE equal to 19.34% and a RMSE equal to 2.11.

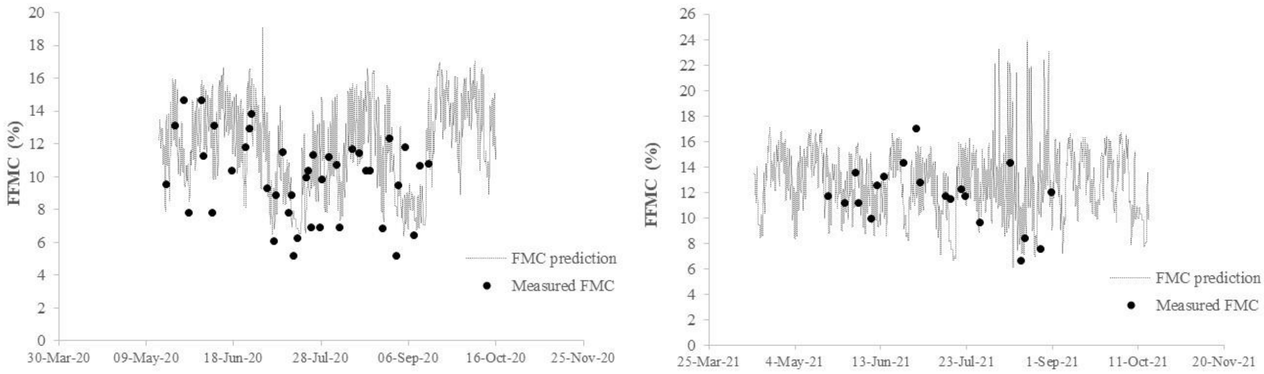


Figure 3- Comparison between the predicted (line) and the observed (dots) FMC of Pinus pinaster branches during 2020 and 2021 (15th May to 15th October). Predicted values result from the Modified Henderson and Pabis model for the drying and wetting curves and the Van Wagner model for EMC.

4. Discussion and Conclusion

The drying and wetting curves of dead *Pinus pinaster* branches (0.6 cm to 2.5 cm diameter) show that they are not pure exponential functions, but with different timelag values until equilibrium is reached. Additionally, the results suggest no significant relationship of the timelag periods with air relative humidity but a dependence with air temperature. An increase in the sorption rates with temperature is observed in this study that is in agreement with the results reported by Byram (1963). However, the pure exponential equation of Byram (1963), that is usually used in forest fire research, does not represent well the drying and wetting curves of dead *Pinus pinaster* branches. Modified Henderson and Pabis model provide the best fitting.

For this type of fuels, the representation of EMC values as a function of air relative humidity at constant temperature allowed to obtain a typical sigmoid curve. The EMC values obtained were higher for desorption process than for adsorption process, indicated the typical hysteresis effect in these processes.

It was found that, besides the models used in forest fires, other EMC models are also suitable to predict fuel moisture content of dead *Pinus pinaster* branches, as the ones used in agricultural and food analysis.

Comparing the predicted and the observed FMC of *Pinus pinaster* branches, the results show a high prediction ability of the best models, with a MAE equal to 1.83%, a MAPE equal to 19.34% and a RMSE equal to 2.11. Lee et al. (2020) and Dios et al. (2015) obtained similar results using other models type with this type of forest fuel (10h-fuels).

5. Acknowledgements

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6. References

Bradshaw LS, Deeming JE, Burgan RE, Cohen JD (1983) The 1978 National Fire-Danger Rating System: technical documentation. United States Department of Agriculture, Forest Service, General Technical Report INT-169. Intermountain Research Station, Ogden, Utah. 44 pages

Byram GM (1963) An analysis of the drying process in forest fuel material. USDA Forest Service, Fire Sciences Laboratory, Rocky Mountain Research Station, Report. (Missoula, MT)

Catchpole E A, Catchpole WR, Viney NR, McCaw WL, Marsden-Smedley JB (2001) Estimating fuel response time and predicting fuel moisture content from field data. International Journal of Wildland Fire 10, 215-222 https://doi.org/10.1071/WF01011

Dios VR, Fellows AW, Nolan RH, Boer MM, Bradstock RA, Domingo F, Goulden ML (2015) A semi-mechanistic model for predicting the moisture content of fine litter. Agricultural and Forest Meteorology 203, 64-73.

Chen CC (1990) Modification of Oswin EMC/ERH equation. Chinese Agricultural Research 39(4), 367–376.

Henderson SM (1974) Progress in developing the thin layer drying equation. Transactions of the ASAE. American Society of Agricultural Engineers 17, 1167–1168. doi:10.13031/2013.37052

Henderson SM, Pabis S (1961) Grain drying theory I: temperature effect on drying coefficient. Journal of Agricultural Engineering Research 6, 169–174.

Iglesias HA, Chirife J (1976) Prediction of the effect of temperature on water sorption isotherms of food materials. Journal of Food Technology 11, 109–116. doi:10.1111/J.1365-2621.1976.TB00707.X

Karathanos VT (1999) Determination of water content of dried fruits by drying kinetics. Journal of Food Engineering 39, 337–344. doi:10.1016/S0260-8774(98)00132-0

Lee HT, Won M, Yoon S, Jang K (2020) Estimation of 10-hour fuel moisture content using meteorological data: A model inter-comparation study. Forests 11, 982. Doi:10.3390/f11090982

Matthews S (2014) Dead fuel moisture research: 1991–2012. International Journal of Wildland Fire 23, 78–92 doi:10.1071/WF13005

Nelson, RM (1969) Some factors affecting the moisture timelags of woody materials. USDA For. Serv. Southeast. For. Exp. Stn. Res. Pap. SE-44

Page GE (1949) Factors influencing the maximum rate of air drying shelled corn in thin-layers. MSc thesis, Purdue University, West Lafayette, IN.

Pfost HB, Maurer SG, Chung DS, Milliken GA (1976) Summarizing and reporting equilibrium moisture data for grains, ASAE paper number 76–3520. (St Joseph, MI)

Rothermel RC (1983) How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 161 p.

Van Wagner, CE (1987) Development and Structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Petawawa National Forestry Institute, Forestry Technical Report 35 (Chalk River, ON)

Viegas DX, Viegas MT, Ferreira AD (1992) Moisture contente od fine forest fuels and fire occurrence in Central Portugal. International Journal of Wildland Fire 2 (4), 69-86.

Viney, NR, & Catchpole EA (1991) Estimating fuel moisture response times from field observations. International Journal of Wildland Fire, 1, 211-214