Moisture Exchange Models for Standing Dead Grass in Alaska

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1 April 2015

Abstract

- Models to predict the moisture content of standing dead grass from weather
- Derived from 6 years of burning on military training ranges
- Models: Existing EMC, Non-linear Regression, Bookkeeping
- Best models are existing EMC equation (1) and non-linear regression models (many)
- Evaluated against an independent data set from Ontario, Canada
- Usable on the fireline and in fire danger rating

Need

Military training activities result in unwanted ignitions
Need:

- Predict moisture content in over-wintered standing dead grass.
- Identify Army training windows
- Rate fire danger
- Predict fire behavior
- Plan with a basis in risk

Objectives

- Produce moisture content models based on environmental measurements
- Merge science from other industries

How do fuels dry?

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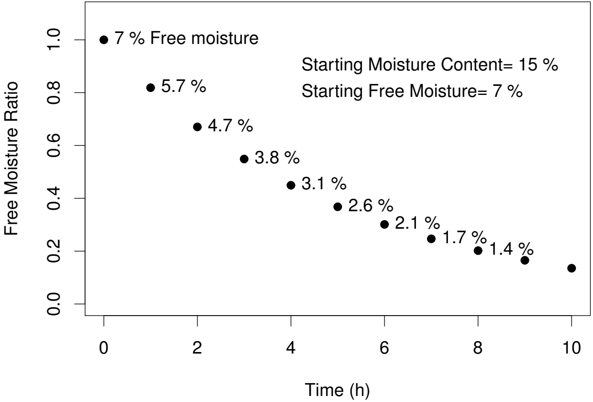
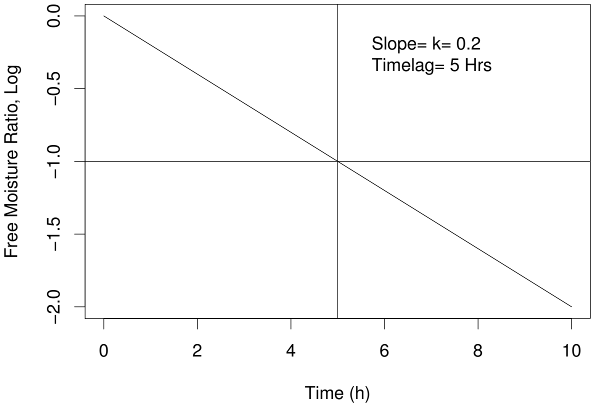
Imagine a fuel at 15% moisture content placed in a climate controlled cabinet where the equilibrium moisture content is 8%
Fuel moisture cannot go below 8% (Equilibrium)
Therefore can only lose 15%-8% = 7%
This is the ‘Free Moisture’ at this T and RH

Log Drying Rate Equation



Log Drying Equation



Drying Equation

$$\frac{F_t}{F_0} = \frac{M_t - M_e}{M_0 - M_e} = e^{-kt} \quad (1)$$

- Backbone of the FWI
- Three measurements
  M_0 = Starting moisture content
  M_t = Ending moisture content at time, t
  t = Elapsed time
- Two unknowns
  M_e = Equilibrium moisture content
  k = Logarithmic drying rate

Look at EMC in more depth...

Equilibrium Moisture Content

Equilibrium moisture content, M_e

No net exchange of moisture between the fuel and the air under a stable air mass

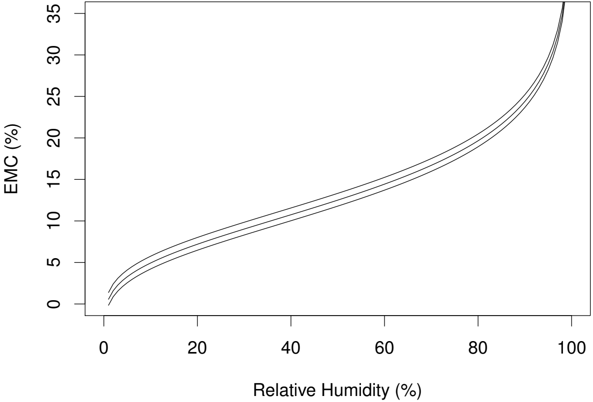
Moisture in = Moisture out

Highly dependent on H_r, less so on T_a

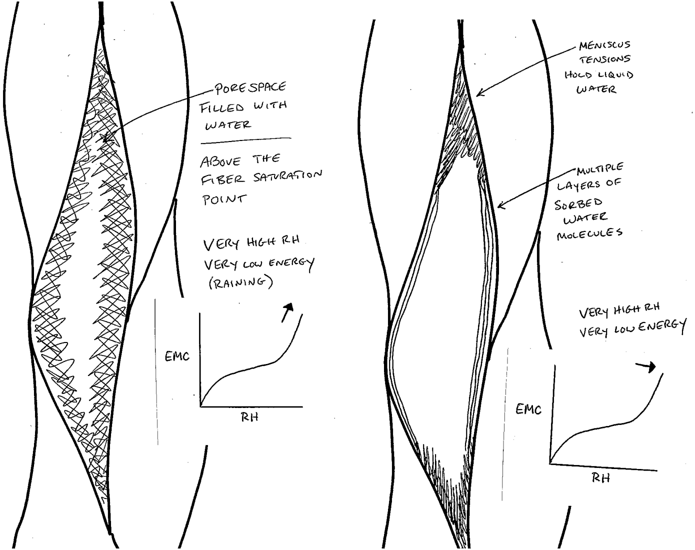
M_e ranges $0 \propto 35\%$

R&D has shadowed along in parallel behind Food Engineering and Agriculture industries

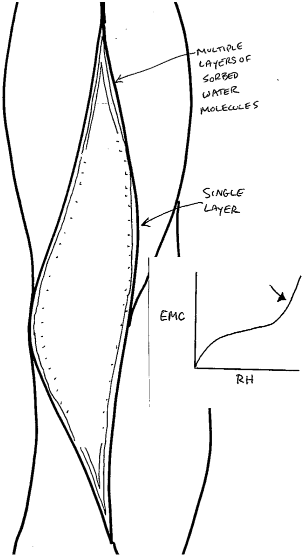
Equilibrium Moisture Content

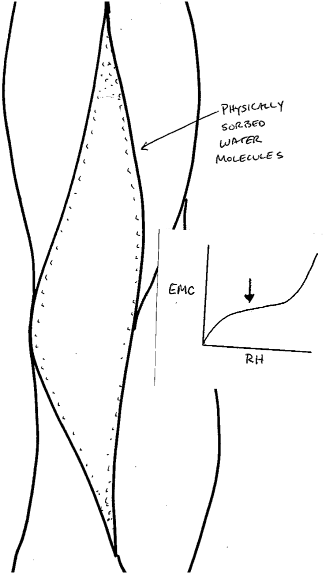


Equilibrium Moisture Content

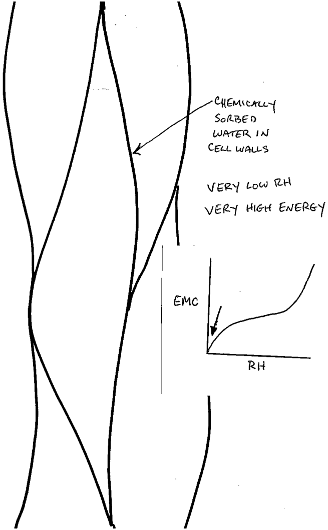


Equilibrium Moisture Content





Equilibrium Moisture Content



M_e Equation Sources

Halsey (1948)

$$M_e = \left(\frac{-e^{a+b\times T_a}}{log(\frac{H_r}{100})} \right)^{\frac{1}{c}} \quad (2)$$

Henderson (1952)

$$M_e = (-\frac{log\left(\frac{1-H_r}{100}\right)}{a(T_a + b)})^{\frac{1}{c}} \quad (3)$$

Chung-Pfost (1967)

$$M_e = a - b \times log\left((T_a + c) \times log\left(\frac{H_r}{100} \right) \right) \quad (4)$$

EMC Equation Sources

Nelson (1983,1984)

$$M_e = \frac{1}{b} \times log\left(\frac{-\mathrm{R} \times T_K}{\mathrm{M_w} \times e^a} \times log\left(\frac{H_r}{100}\right)\right) \quad (5)$$

Not 'Modified' with a coefficient on temperature

The only truly physical-based equation

EMC Equation Sources

Anderson (1990). Fit coefficients a and b in Nelson's equation with regressions on temperature, Kelvin.

$$a = c_1 + c_2 \times T_K + c_3 \times T_K^2 \tag{6}$$

$$b = c_4 + c_5 \times T_K + c_6 \times T_K^2 \tag{7}$$

EMC Equation Sources

Van Wagner (1972):

$$M_e = a \times H_r^b + c \times e^{\left(\frac{H_r - 100}{d}\right)} + 0.27 \times (26.7 - T_a) \times \left(1 - e^{-0.115 \times H_r}\right) \quad (8)$$

The only empirical (non-thermodynamic) equation
Developed at 80°F; Corrected to other temperatures
Clunky!
Used extensively in the FWI.

EMC Equation Sources

EMC equations vary in:

- Physical vs Semi-physical vs Empirical
- Food engineering/Agriculture vs Forestry Industries
- Numbers of coefficients (2-6)

All utilize H_r and T_a

Types of Moisture Models

Moisture Content = f(Some phenomena)

- Empirical. Merely fit coefficients without regard to physics or process
- Process-based. Attempt to model the physics and processes involved
- Blend
- Models of each presented

Field Methods

- Burns in Delta, Anchorage, Fairbanks 2009-2014
- FEMO duties
- Measure weather
- Measure moisture content
- Relate weather to moisture content
- n=285

Basic statistics

Min.	Mean	Max.	Units	
M_t	4.0	10.8	29.0	%
Time of Day	5:30	14:16	21:40	
Elapsed Time	0:05	1:11	3:00	h
T_a	26	53	86	°F
T_a	-3.3	11.7	30	°C
H_r	14	34.8	83	%
U_{el}	0	4.9	16.3	$\mathrm{km\,h^{-1}}$
Cloud Cover	0	39	100	%
Solar elevation	-1.4	33.5	49.8	deg

Linear Regression

Started with linear regression

$Mt = a + bx$

$Mt = a + bx_1 + cx_2$

Significant models:

- Temperature
- Dew point
- Relative humidity
- Temperature + Dew point
- Temperature + Relative humidity
- Cloud cover
- Me (Equilibrium moisture content)

Models were significant but awkwardly fit or significant but not useful

Linear Regression

Two models suggested a non-linear, sigmoidal curve

$Mt = a + b \times H_r + c \times T_a$

Residual plot suggested a non-linear regression

$Mt = a + b \times M_e$

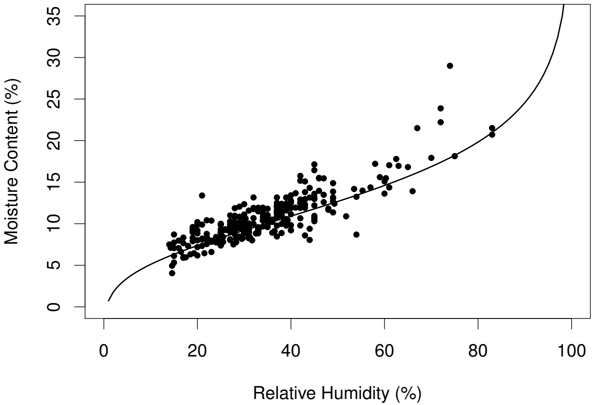
Slope $\propto$ 1 and Intercept $\propto$ 0 suggests:

$Mt = M_e$

Linear Regression Inferences

At this point linear regression wasn't working.
A non-linear M_e equation form should work.
Why? M_t lags very close to M_e.
1. Would an 'Out-of-the-box' M_e equation work?
2. Fit custom coefficients to an M_e equation form

M_t closely lags M_e



Raw M_e Equations

- Anderson (1990), Cheatgrass, Weathered&Recently cast
- Van Wagner (1972) Grass
- Nelson (1984) Wiregrass
- Duggal (1981) Wheat straw, (Adsorption only)

Raw M_e Equations

Anderson (1990)

- 3 of 4 equations had very poor fit
- Modal with temperature
- Probably over-fit equation form (5-6 coefs)
- Recently cast cheatgrass desorption equation fit very well. Accident?

Raw M_e Equations

Van Wagner (1972)

- Very poor fit.
- Reasonable at development temperature, 80°F
- Very poor fit at low temperature in the Alaska dataset 53°F
- Incorrect temperature correction term
- Probably overfit (4 coefs)

Raw M_e Equations

Nelson (1984)

- Moderate to poor fit
- Under-fit. No coefficient on temperature limits its ability to absorb error
- Developed at 80°F

Raw M_e Equations

Duggal (1981)

- Only an adsorption equation available
- Wheat straw $\neq$ Alaska grasses?

Raw M_e Equations

Summary:
Only one raw M_e equation gave reasonable fit
Next, empirically fit M_e equation forms with new coefficients

Fit M_e Equation Forms

Equation forms selected:

- Halsey
- Henderson
- Chung-Pfost
- Nelson

All thermodynamic, 2-3 coefficients
Not selected:

- Anderson (6 coefficients. Weak physical basis.)
- Van Wagner (4 coefficients. Clunky. No physical basis)

Non-linear models fit using Levenberg-Marquardt algorithm in R for Statistical Computing (minpack.lm package)

Fit M_e Equation Forms

Selected M_e equation forms performed reasonably well.

Two-factor Nelson equation performed the poorest.

Ranks changed slightly when compared to the Ontario dataset

Take your pick.

All regression models carry a desorption phase bias

Bookkeeping

Next I sought a bookkeeping method after the FWI
Based on the Log Drying Rate Equation.
Iteratively adjusts the trajectory of M_t toward M_e.
Used the same non-linear curve fitting algorithm.

Bookkeeping

$$\frac{M_t - M_e}{M_0 - M_e} = e^{-kt} \tag{9}$$

- Three measurements: M_0, M_t and t
- Two unknowns: M_e and k
- Substitute an M_e equation and solve for M_t
- Selected the Chung-Pfost M_e equation form

$$M_e = a - b \times log\left((T_a + c) \times log\left(\frac{H_r}{100}\right)\right) \tag{10}$$

- Simultaneously solve for a, b, c and k

Bookkeeping

- Log drying rate, $k = 0.49$
- Response time, $1/k = 2.0$ h
- Disappointing results. The bookkeeping model predicts no better than the other models
- Why?
  - • Not a repeated measure sampling scheme
  - • Too much landscape heterogeneity
  - • Sampling error leads to free moisture ratios that are impossible under the assumptions of the Log Drying Rate Equation
  - • Sampling error $>$Time-lag
- May work better under adsorption conditions

Rule of Thumb

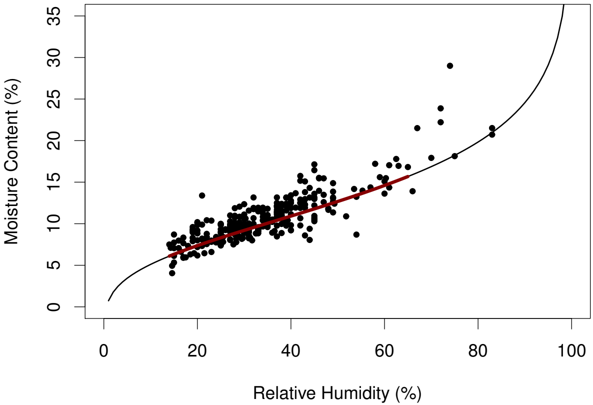
Convenience model
Linear 'Rule of Thumb' Model
Selected H_r 14-65%
Linear regression yielded a slope and intercept of 0.18 and 4.3

$$M_t = \frac{H_r}{5} + 4 \tag{11}$$

Example:

$$\frac{30\%}{5} + 4 = 10\% \tag{12}$$

Rule of Thumb



Model Rankings

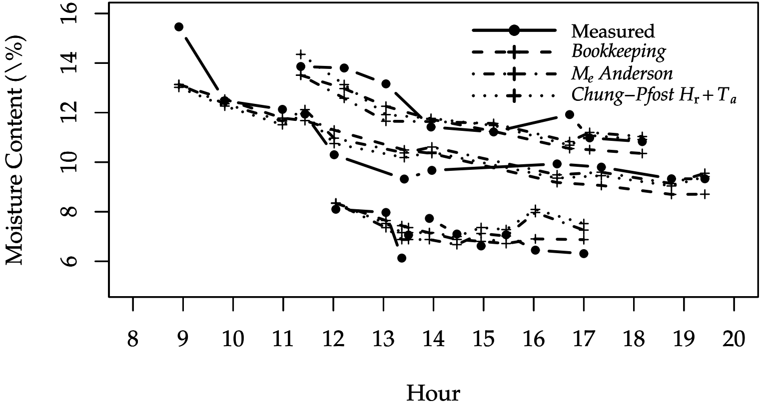
Model	r	RMSE	n
Anderson M_e**	0.883	1.473	285
Chung-Pfost $H_r + T_a$***	0.877	1.485	285
Bookkeeping*	0.885	1.494	285
Halsey $H_r + T_a$**	0.874	1.502	285
Henderson $H_r + T_a$**	0.869	1.531	285
Nelson $H_r + T_a$	0.866	1.549	285
Linear H_r Rule of Thumb*	0.852	1.631	285

My picks:***Best, **Good, *Specialty

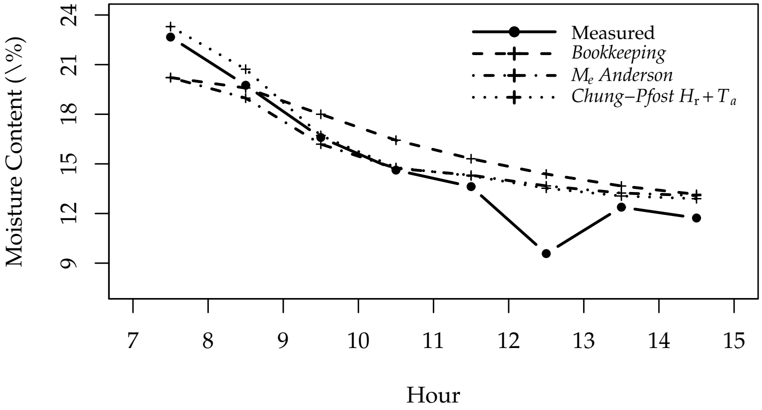
Take-Aways

- 90% of obs between 5.7 and 15.9% moisture content
- Best model was an existing M_e equation. Accident?
- All three-term, thermodynamic non-linear regression models performed well (Halsey, Henderson, Chung-Pfost)
- The bookkeeping method works but offers no advantage
- Rule of thumb model is reasonable in the range of H_r typical of Rx burning
- Some models derive from other industries

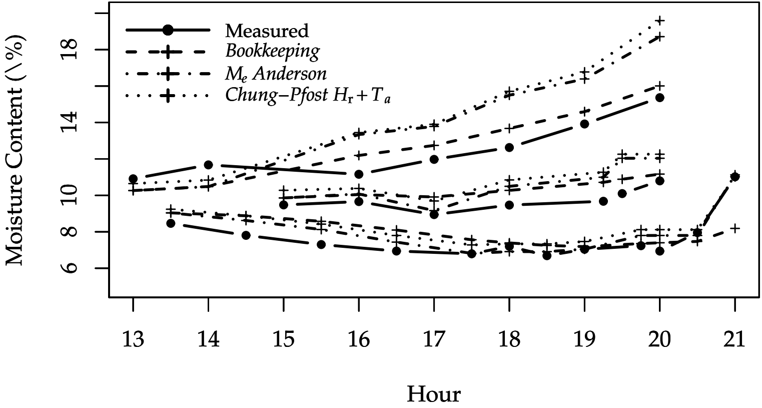
Delta Junction, Alaska



22 May 2006, Ontario, Canada



17, 23, and 24 May 2006, Ontario, Canada



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- Web forecaster for Military Training Ranges in Alaska
- Web calculator for any U.S. Lat-Long
- Manual calculator
- Field tables (Appendix B style)

Next

Next

- Rainfall routine
- FWI Code
- Probability of ignition
- Fire behavior threshold at lower M_e inflection?

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