Comparing Measured Duff Moisture with a Water Budget Model and the Duff and Drought Codes of the Canadian Fire Weather Index

Edward A. Johnson, David M. Keith, and Yvonne E. Martin

Abstract: Fuel moisture plays an important role in predicting wildfire spread rates, fuel consumption, and heat output. The purpose of this study was to find how much we can simplify an F and H layer moisture model by comparing an empirical-phenomenalistic drying model with a mechanistic water budget that included all of the major water fluxes. Traditionally, fuel moisture has been calculated using phenomenalistic exponential drying rate models, which use standard meteorological station variables (temperature, precipitation, relative humidity, day length, and others). First, we report on comparisons between field-measured F and H soil layer moisture and moisture estimates based on the Duff Moisture Code and Drought Code of the Canadian Forest Fire Weather Index (FWI) in Pinus contorta and Picea engelmannii forests during dry and wet years. Next, an F and H layer water budget is used to understand possible reasons for the differences between the Duff Moisture Code, the Drought Code, and the moisture measured in the field. For the pine forest, the Duff Moisture Code was a good estimate of the F layer moisture during and shortly after precipitation events in both the dry and wet years but underestimated moisture when duff was drying. The pine Drought Code underestimated the H layer moisture in the dry year and overestimated it in the wet year. For the spruce forest, in the dry year the Duff Moisture Code overestimated the moisture during and after precipitation and underestimated it in dry periods. However, in the wet year, the code overestimated moisture most of the time. The spruce Drought Code underestimated the moisture content in both the wet and dry years. Results from the water budget model suggest that the difference in the F layer moisture between the field measurements and both the Drought Code and Duff Moisture Code is due to the lack of coupling of water flow between the F and H layers in the codes. In particular, the diurnal water movement from the H to F layer during the drying part of the season is integral to the water budget. To improve predictions based on the fuel moisture codes, coupled water and heat budgets along with the hydrologic properties of the F and H layers should be incorporated into the codes to enable more accurate prediction of duff moisture and calibration for different types of duff. For. Sci. 59(1):78–92.

Keywords: wildfires, duff codes, drought codes, Fire Weather Prediction System, duff, water budget

The amount of the forest floor F and H organic layers removed by smoldering combustion during wildfires (Miyanishi 2001) is a major control of the regeneration of trees (Chroszciewicz 1959, 1970, 1974, 1976, Zasada et al. 1983, Thomas and Wein 1985, Charron and Greene 2002). Both the H layer and the underlying mineral soil provide a better seedbed for seedlings than the F layer because of their greater water-holding capacity. There is also some evidence that the remaining duff after a fire may be important in preventing erosion by both affecting ponding rates and providing resistance to overland flow (Martin et al. 2011).

Duff consumption by smoldering results in a spatial pattern owing to the interaction of hillslope position and shape (i.e., whether the slope is convergent or divergent), the amount of precipitation and the time since the last precipitation event, the forest canopy composition and density (as they affect the interception of precipitation), and the depth of the duff layer (Miyanishi and Johnson 2002). Combinations of these factors result in some wildfires removing duff only under the canopy, whereas in other fires, the duff is completely removed everywhere. Smoldering in the F and H layers is primarily controlled by their bulk density, depth, and moisture content (Miyanishi 2001). Of these factors, moisture content is the most variable and, thus, is a critical component of wildfire weather indexes.

In a multiyear study of a jack pine (Pinus banksiana Lamb.) forest, Wotton et al. (2005) found that the forest canopy interception of precipitation had a small scale (within meters) effect on water input to the forest floor. Raaflaub and Valeo (2008), Keith et al. (2010a, 2010b), and L.D. Raaflaub et al. (2012) monitored the spatial variation in the F and H layer moisture in situ in lodgepole pine (Pinus contorta Dougl.) and Engelmann spruce (Picea engelmannii Parry) subalpine forest stands. On both pine and spruce hillslopes, canopy interception accounted for significant variation in moisture at the scale of a few meters or less. At the larger hillslope scale, atmospheric (evaporation) processes were the primary causes of moisture variation in the pine stand with greater evaporative fluxes occurring on the drier south-facing aspects. On the pine hillslopes, the canopy structure and small macropores in the thin F and H

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layers may have accounted for the lack of significant lateral flow in the organic layers. On the spruce hillslopes, lateral flow was more important than atmospheric processes, possibly due to larger macropores in the thicker F and H layers and different canopy structure. On both pine and spruce hillslopes, there was no evidence for large networks of connected macropores in the F and H layers; only small networks of short macropores led to redistribution of water (Keith et al. 2010a).

Keith et al. (2010a, 2010b) found that the mechanisms driving moisture distribution in the F and H layers varied between “wet” and “dry” periods. In wet periods, both vertical and lateral movement strongly influenced the water budget with negative net lateral water fluxes in divergent areas of the hillslopes and positive fluxes in convergent areas. In these periods, precipitation drives flow into the F layer, downward from the F into the H layer, laterally into the F and H layers, and downward from the H layer into the mineral soil. Dry periods occur when there is minimal lateral flux in either the F or H layer or little infiltration from the H layer into the mineral soil. During this dry period, the duff is spatially isolated with only vertical flow occurring that is driven predominately by evaporation; there also appears to be little influence of transpiration on either F or H layer moisture content. Evaporative fluxes coupled with the moisture gradient within the duff result in a diurnal cycle in the F layer moisture content during dry periods. The H layer acts as a source of water for the more rapid evaporative loss from the F layer. Significant vapor and liquid fluxes occur during the afternoon when the moisture and thermal gradients between the F and H layer peak; the net result is a decrease in moisture in both the F and H layer during the day. In the morning, moisture increases slightly in the F layer as liquid and vapor transfer continues from the H layer into the F layer, creating the diurnal cycle. The predominance of vertical flow during the dry period reinforces the patchy pattern of moisture created during the wet periods due to local slope curvature (convergent/divergent), canopy or gap location (precipitation interception), hydrologic conductivity, and depth of the F and H layers. This one-dimensional moisture movement has been called “local control” in mineral soils by Grayson et al. (1997). The combination of redistribution during wet periods and local control thereafter appears to be responsible for the patterns of duff consumption observed in wildfires (e.g., Miyaniishi and Johnson 2002, Zasada et al. 1983, and others).

This seasonal variation in F and H layer moisture content is influenced by the amount of and time since last precipitation, hillslope position, and canopy position. These results raise two general questions: First, is a distributed hydrologic model needed to accurately estimate the F and H layer moisture content for a watershed due to the multiscale variation in duff moisture? The level of distribution in the model will depend on the scale of the question. For example, someone interested in predictions of forest floor moisture to ensure tree regeneration in a prescribed burn may want a prediction of moisture at the scale of meters, whereas someone in wildfire suppression may be willing to have a reasonable average prediction for the whole watershed. Second, at the stand and hillslope scale, how simple a model is required to accurately predict F and H layer moisture? Empirical-phenomenalistic drying models, which relate moisture to temperature, humidity, and precipitation, have generally been used to estimate F and H layer moisture. These models use weather stations for the climate data (as a rule of thumb they should be within about 50 km of the studied location) along with general characteristics of the forest floor fuels.

The purpose of this article was to determine how much a moisture model can be simplified by comparing a relatively simple empirical-phenomenalistic drying model with a more complicated mechanistic water budget, which includes all of the major water fluxes. The simple empirical-phenomenalistic drying model will first be compared with the measured moisture content of the F and H layers. Then, the water budget model will be used to examine what mechanism(s) may be leading to the deviation between the measured water content of the F and H layers and values predicted from the empirical-phenomenalistic drying model. Specifically, the objectives of this article were the following: to determine how the measured temporal variation in the forest floor F and H layer moisture content compares with the predicted Duff Moisture Code and Drought Code of the Canadian Forest Fire Weather Index (FWI), which is an empirical-phenomenalistic drying model; and to use a coupled F and H layer water budget model (Keith et al. 2010a) to determine what mechanisms lead to the differences between the empirically measured water content and values predicted by the Duff Moisture Code and Drought Code. The following comparisons are made: empirical moisture measurements of F and H layers are compared with the Duff Moisture Code and Drought Code, respectively, using weather data collected at the pine and spruce sites of the empirical measurements and the procedures of the Canadian Forest Fire Weather Index System (Van Wagner 1987, Hirsch 1996); and water budget simulation results for the F and H layers are compared with the Duff Moisture Code and Drought Code, respectively, using weather data from the same pine and spruce sites.

Models of F and H Layer Moisture

**Empirical-Phenomenalistic Drying Model in the Moisture Codes of the Canadian Forest Fire Weather Index**

The FWI system (see Van Wagner 1987, Hirsch 1996) defines three moisture codes: Fine Fuel Moisture Code, Duff Moisture Code (DMC), and Drought Code (DC). Here, we consider only the DMC and DC. The DMC was originally developed in pine stands in Petawawa, Ontario, Canada, in which the duff layer was considered the F layer as defined by soil scientists (Canada Soil Survey Committee 1978). The DMC is defined for loosely compacted, decomposing organic matter with a nominal depth of approximately 7 cm and bulk density of 71 kg m\(^{-3}\). The DMC has an expected time lag to reach 63% moisture of 12 days.

The DC was originally developed and calibrated for balsam fir and upland black spruce stands in Ontario, Canada. In general, the DC corresponds to the H layer when...
present and represents moisture in the deeper layers of compact organic matter with a depth of approximately 18 cm and bulk density of 140 kg m$^{-3}$. The DC has an expected time lag to reach 63% moisture of 52 days. The DC has sometimes been considered to represent moisture in other large dead organic fuels. It has even been suggested that it can be used to assess the mineral soil water content (Turner 1972).

The DMC and DC are not water budgets in that they do not measure the fluxes of water into and out of fuel nor do they incorporate process equations responsible for these fluxes (Figure 1). These codes do not consider the mechanisms controlling the water budget but instead relate the moisture content to forcing variables (e.g., temperature, humidity, precipitation, and others). This phenomenological approach is typical in the initial study of a complex set of processes. During the era of the development of the FWI (1960s–1970s), there was a need for straightforward procedures that could be applicable in a range of situations. In particular, given the constraints of computing power at the time, it was important that approaches not require complicated calculations or field deployment of instrument arrays beyond standard meteorological stations.

We have since developed a more complete understanding of how the processes (mechanisms) of wetting and drying occur in the organic fuel and how the water content of the organic fuels affect and are affected by (coupled to) their surrounding fuels, atmosphere, and soil. This knowledge, when coupled with increased computing power and the ability to deploy more diverse instruments in the field, suggests that more accurate methods of calculating duff moisture content using water budgets should be pursued. At a minimum, a detailed understanding of the processes influencing the water budget can be used as a tool to measure the effectiveness of more heuristic approaches and to suggest how to improve the accuracy of the existing codes.

![Figure 1. Model of water budget for the F and H duff layers and the mineral soil.](image-url)
Empirical drying of organic material is usually given as gravimetric water \((w)\) content plotted against time (Figure 2a). Two periods of drying can be identified by plotting either the drying rate against moisture \((w)\) (Figure 2b) or the drying rate against time (Figure 2c). These two latter graphs show two distinct periods: a constant rate that occurs when the surface where the water is being lost is saturated and evaporation, not the internal structure of the material, controls water loss; and a falling rate that occurs when the surface is no longer saturated and the equilibrium moisture content (EMC) depends on temperature and humidity.

The FWI system (for details and equations, see Van Wagner (1987) and Hirsch (1996)) approximates drying by using the falling rate because the water content of the organic material is almost always in the region of the falling rate.

The falling rate can be approximated by an exponential equation and is given as

\[
\frac{dw}{dt} = k \left( \frac{w - EMC}{w_{\text{max}} - EMC} \right)
\]

(1)

where \(w_{\text{max}}\) is the maximum moisture content possible. Solving for gravimetric water content \((w)\) gives

\[
\left( \frac{w - EMC}{w_{\text{max}} - EMC} \right) = \frac{1}{k} e^t
\]

(2)

The drying time is given by

\[
t_r = \frac{1}{k} \ln \left( \frac{w - EMC}{w_{\text{max}} - EMC} \right)
\]

(3)

**Duff Moisture Code**

In the FWI DMC, \(k\) is directly proportional to temperature \((T)\), relative humidity \((H)\), and day length \((L_e)\) and is defined by the empirical relationship:

\[
k = 1.894(T - 1.1)(100 - H)L_e \times 10^{-6}
\]

(4)

The drying is assumed to be exponential with constant \(k\) (i.e., temperature and humidity) and with EMC = 20% over the measurement period. Wetting and drying of the duff are assumed to have no hysteresis. The rewetting is by precipitation not by lateral or vertical flow of water in the layer. Precipitation \((r_e)\) is given as a proportion of the total observed \((r_o)\) at a standard weather gauge in the open by

\[
r_e = \begin{cases} 
0 & \text{for } r_o < 1.5\text{mm} \\
0.92r_o - 1.27 & \text{for } r_o \geq 1.5\text{mm}
\end{cases}
\]

(5)

The moisture content of duff after rain \((M_r)\) is calculated as

\[
M_r = M_0 + 1000 \left( \frac{r_e}{48.77 + b r_e} \right)
\]

(6)

where \(b\) is an empirical coefficient \((b = 14 - 1.3 \ln P_0\) when \(33 < P_0 \leq 33; b = 100(0.5 + 0.3 P_0)\) when \(P_0 \leq 33)\) depending on the range of the previous day’s moisture code \((P_0)\), and

\[
M_0 = 20 + e^{\left( \frac{5.6348 - P_0}{3.45} \right)}
\]

(7)

The DMC after rain is

\[
P_r = \begin{cases} 
244.72 - 43.43 \ln(M_r - 20) & \text{if } P_r > 0 \\
1 & \text{if } P_r = 0
\end{cases}
\]

(8)

This relates the moisture content to the Code \(P_r\). Thus, the DMC is

\[
P = \frac{P_0}{P_r + 100k}
\]

(9)
Drought Code

The DC is constructed in a manner to that for the DMC except that a seasonal, startup strategy is required (here we just used the actual H layer moisture). The DC becomes the previous day \( D_0 \) if no rain or \( D_t \) if rain on the previous day:

\[
D = \begin{cases} 
D_0 & \text{if no rain} \\
D_t + 0.5V & \text{if rain on the previous day}
\end{cases}
\]  
(10)

The potential evapotranspiration term \( (V) \) depends on an empirical relationship that is proportional to temperature \( (T) \) and day length factor \( (L_d) \):

\[
V = 0.36(T + 2.8) + L_d 
\]

if \( V < 0 \) let \( V = 0; T < -2.8 \) must not be used.  
(11)

The wetting phase uses an effective rainfall:

\[
r_d = \begin{cases} 
0 & \text{for } r_o < 2.8 \text{mm} \\
0.83r_o - 1.27 & \text{for } r_o \geq 2.8 \text{mm}
\end{cases}
\]
(12)

and the moisture equivalent \( (Q_t) \) after rain is proportional to the effective rainfall \( r_d \) using

\[
Q_t = Q_0 + 3.93r_d 
\]
(13)

where \( Q_0 = 800e^{-D/400} \). The DC then in terms of moisture equivalence \( (Q_t) \) is

\[
D_t = 400\ln(800Q_t). 
\]
(14)

Notice that this moisture equivalence is in mm of water (i.e., volumetric, not gravimetric [% dry weight], water content).

Coupled F and H Layer Water Budget Model

The DMC and DC can be expanded beyond their empirical forcing variables to include the internal mechanism of water movement in the duff and soil. One way to accomplish this is by invoking a water budget (Keith et al. 2010a, 2010b). Here we consider the F layer moisture to be represented by the DMC and the H layer moisture to be represented by the DC. This is not an ideal match to the FWI, particularly of the DC to the H layer, given the imprecise definition of what the fuel is. Nevertheless, it will help make explicit the coupling of the F and H layers and the connection of surface evaporation from the F layer, lateral flow into and out of the F and H layers, and the mineral soil.

The water content of the F and H layers can be modeled by a coupled energy (heat) and mass (water) budget (Figure 1). The moisture content of each layer is equal to the water fluxes into and out of that layer. The vapor and liquid water that accumulates in a layer depends on its porosity. The fluxes in a layer are calculated using a multiphase version of Darcy’s law. Unsaturated flow is driven by gravity and matric potential. Precipitation and evaporation add or remove water, respectively, from the surface of the F layer. Energy (heat) accumulation in a layer takes into account the thermal properties, temperature, and amount of liquid and vapor in the pore spaces. The energy accumulated by the layer will vary with temperature, whereas the energy in the pore space depends on the quantity and temperature of vapor and liquid within the pores. The energy flux within the duff is modeled by conductive and convective processes between layers and is dependent on the thermal properties and the temperature gradient. Convective through the duff is due to energy flux resulting from the movement of vapor and liquid. Details regarding this budget, the numerical methods, parameters, and the boundary conditions can be found in the Appendix (Table A1).

Field Methods

The empirical data were collected in the Marmot Basin Research Watershed located in the Kananaskis Valley, Alberta, Canada (NAD83 11U 629800 5645900). The watershed covers approximately 9.6 km², with a range in elevation from 1,585 to 2,838 m. The climate in the region is characterized by long, cold winters and cool summers. Annual precipitation in the watershed ranges from 660 mm near the outlet to more than 1,100 mm at high elevations (Stevenson 1967). Historically, 70–75% of the precipitation falls as snow.

The majority of the moisture input is due to snowmelt and precipitation during the spring and late summer, with May and June experiencing the most precipitation. The basin dries out throughout the remainder of the summer, with the main input being rainfall associated with convective storms.

The basin’s outlet stream is fifth order, and flow out of the basin has been measured between May and October since 1964 at a v-notched weir. Peak discharge from the basin occurs in June, with a maximum instantaneous flow rate of 3.4 m³ s⁻¹ and mean daily average flow varies from a low of less than 0.1 m³ s⁻¹ during the fall to a high of 0.65 m³ s⁻¹ in June.

The forest cover within the basin consists primarily of conifers. The upper subalpine forest, from approximately 1,700 to 2,200 m, consists of Engelmann spruce (P. engelmannii) and subalpine fir (Abies lasiocarpa [Hook.] Nutt.). The lower subalpine forest, below 1,700 m, is dominated by lodgepole pine (Pinus contorta var. latifolia) and Engelmann spruce. The duff layer is found throughout the forested parts of the watershed, the thickness of the layer varying from as little as 4 cm in lodgepole pine stands to 30 cm under the canopy in both the spruce and fir stands. The mineral soil in the forested part of the basin consists largely of well-drained Podzolic soils. The basin is covered by glacial tills to a depth of approximately 10 m, with an infiltration rate much greater than peak storm intensity (Stevenson 1967). Field data were collected from mid-May until early September 2007 and 2008 in a P. contorta stand at elevation of 1,393 m and a P. engelmannii stand at elevation 1,852 m. For more information on the stands and the F and H layer moisture content during spring and summer on the hillslopes, see Keith et al. (2010a, 2010b).

Average duff bulk density in the pine stand was 101 kg m⁻³ for the F layer and 165 kg m⁻³ for the H layer; in the spruce stands, the average bulk density was 110 kg m⁻³ for the F layer and 150 kg m⁻³ for the H layer. Soil moisture was measured at five depths using a Theta Probe (Delta-T Devices): F layer 2 cm below surface, H layer 2 cm above bottom of duff, mineral soil 5 cm below bottom of duff, mineral soil 15 cm below bottom of duff, and mineral soil
vaporization, and underestimated it during the drier periods. The pine F layer increased quickly during precipitation and dried throughout these dry and wet years, the DMC-M for the wetter summer of 2008, the DMC-M underestimated the consistently higher until after August 21. Thus, during theiture after August 9, whereas in 2008, it did not become.

In both the drier (2007) and wetter (2008) years, the pine stand’s H layer moisture predicted by the DC (DC-M) was consistently lower than the measured moisture during the wet part of June and during the drier August period (Figure 4). The small precipitation events in July largely affected the F layer moisture and do not appear to have infiltrated into the H layer with the exception of the July 19 spike in 2007. This spike may be due to a preferential flow channel observed at times when the layers were dry. However, the larger precipitation events in August 2007 and July 2008 did result in increases in both the DC-M and measured moisture. In the wetter year of 2008, the DC-M was higher than the measured moisture in June and July.

In the pine stand, the possible reason for the lower values of the DMC-M compared with the measured F layer moisture is the assumption in the DMC and DC that the F and H layers are not coupled. Thus, the vertical movement of water from the H to the F layer observed in the hourly measurements during drying by Keith et al. (2010a) may be the reason for the downward bias in the DMC-M. To test this hypothesis, we used the Keith et al. (2010a) water budget model modified so that the F layer has no lateral flow from adjacent F layers and no vertical flow from either the H layer or mineral soil. If this hypothesis is correct, these modifications should duplicate the formulation of the DMC, which includes only precipitation inputs and drying losses, with no movement of water from the H layer. In this test we focused on two drying periods (July 2–16 and July 21–Aug. 4, 2007) when the F and H layer coupling was shown to be significant (Keith et al. 2010a). Furthermore, in dry periods, water does not generally move laterally or from the mineral soil upwards into the F and H layers; thus, during this period the F and H layer coupling is the primary mechanism along with evaporation that is responsible for moisture redistribution in the drying phase of the duff. The results of this test (Figure 5a) show that the simple one-dimensional model water budget gives trends that are more or less similar to those for the DMC-M. The small precipitation event on July 9 (3.2 mm) moved the absolute value of the DMC so that it underestimated before the precipitation and overestimated after the precipitation.

To simulate the overestimate of DC-M in the pine stand during periods with no precipitation (drying periods), the Keith et al. (2010a) water budget’s vertical flow of liquid and vapor from the H to F layers was removed, and vertical flow from the H layer was driven by evaporation (Equation 15), i.e., as if the F layer was not there. The result of this simulation (Figure 5b) indicates that the overestimation of the DC-M is partially due to the exclusion of both the F

\[ E_v = 3.6 \times 10^9 \left( \frac{\delta E}{\rho L} \right) \]  

where \( \rho \) is the density of water, \( L \) is the latent heat of vaporization, and \( \delta \) is the duff moisture deficit:

\[ \delta = \frac{\theta - \theta_s}{\theta_{\text{max}} - \theta_s}. \]

Model Comparison

Our objective relates to comparisons of the trends, not the goodness of fit, because our interest is in how simplified a model of the F and H moisture can be made on the continuum from empirical-phenomenalistic to a more mechanistic water budget.

Results

First, we compared the measured F layer moisture with the predicted DMC in the lodgepole pine stand (Figure 3) and then the measured H layer moisture with the predicted DC (Figure 4). The dry period from June 19 to July 31, 2007, had lower precipitation (23.2 mm) than the similar period in 2008 (39.6 mm); thus, 2007 was considered a drier year than 2008. In both 2007 (Figure 3a) and 2008 (Figure 3b), the pine stand’s F layer moisture predicted by the DMC (DMC-M) had similar trends but was systematically lower than the measured gravimetric moisture through the wet period in June and the dry period from late June to the end of July (except for a few days around July 20 associated with 2 days of rain in both years). In addition, in 2007, the DMC-M was systematically higher than the measured moisture after August 9, whereas in 2008, it did not become consistently higher until after August 21. Thus, during the wetter summer of 2008, the DMC-M underestimated the measured moisture most of the time (Figure 3b). Overall, throughout these dry and wet years, the DMC-M for the pine F layer increased quickly during precipitation and dried more rapidly compared with the measured moisture. The DMC-M often overestimated the F layer moisture during wet periods and underestimated it during the drier periods.

The underestimation of duff moisture was more consistent during the wet year of 2008 as might be expected because it was designed to operate best under dry conditions in which wildfires were more likely.

The DC was designed to provide the volumetric moisture when it was originally developed (Turner 1972). The conversion from measured gravimetric to volumetric water content (to be comparable to the DC moisture) makes only a small change in values and does not change the relative behavior. In both the drier (2007) and wetter (2008) years, the pine stand’s H layer moisture predicted by the DC (DC-M) was consistently lower than the measured moisture during the wet part of June and during the drier August period (Figure 4). The small precipitation events in July largely affected the F layer moisture and do not appear to have infiltrated into the H layer with the exception of the July 19 spike in 2007. This spike may be due to a preferential flow channel observed at times when the layers were dry. However, the larger precipitation events in August 2007 and July 2008 did result in increases in both the DC-M and measured moisture. In the wetter year of 2008, the DC-M was higher than the measured moisture in June and July.

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layer moisture coupling to the H layer and thermal insulation of the F layer to the H layer. The DC uses a measure of potential evaporation (Equation 11) that is an empirical relationship between temperature and day length. It also requires that the user supply a start-up value in the beginning of the season (see Turner and Lawson 1978); in our study, we used the measured H layer moisture so as not to confound the results with different start-up strategies.

We repeated all of these analyses in the Engelmann spruce stand (Figures 6–8). In the drier year of 2007 (Figure 6a), the DMC-M predicted the trend in empirical moisture of the F layer reasonably well in June, underestimated it in July, and overestimated it in August. This result is similar to the pattern and moisture percentage of the DMC-M in the pine site for the same year (Figure 3a). In the wetter year of 2008 (Figure 6b), the spruce site’s DMC-M overestimated moisture in June, underestimated it in July, and predicted it well in August. Although the moisture contents were similar for the pine and spruce sites, the 2008 spruce site DMC-M showed somewhat more erratic predictions than the consistent underestimation of the DMC-M for the pine site. For both 2007 and 2008, the DC-M in the spruce site (Figure 7) predicted well the empirical moisture in June but underestimated it in July and August.

Again, we used the water budget model to simulate the DMC-M without either the H layer coupling or lateral flow.
The DMC-M and simplified water budget are very similar in both wet and dry years (Figure 8a). As in the pine stand simulation (Figure 5b), the result in the spruce stands (Figure 8b) showed that the DC-M was higher than the model values, suggesting that the F layer coupling and thermal gradient are in part causing the difference between the DC-M and measured H layer moisture.

Discussion

The DMC and DC were developed to estimate moisture content in two classes of generalized fuels based on their drying rates, using data from regional weather stations. These values of fuel moisture were then combined to give correlations with fire spread and heat output (intensity) indexes (Hirsch 1996). All of these indexes are empirical, requiring easily measured forcing variables for their calculation. At the time of the development of the FWI, computational limitations resulted in foresters adopting these lumped phenomenalistic models. Moreover, the FWI moisture codes are independent of each other. Such approaches did not include the mechanisms that cause changes in fuel moisture and were intended to provide predictions of fuel moisture at regional scales and not at smaller scales in lower-order drainage basins and hillslopes. Use of a water budget model can provide more accurate and detailed predictions because it includes (1) most, if not all, of the input

![Figure 4](https://example.com/figure4.png)

Figure 4. Pine site H layer measured moisture content (m³ m⁻³), predicted DC-M content (m³ m⁻³), and precipitation (mm) during the June–September period for 2007 (a) and 2008 (b).
and output flow terms, (2) initial and boundary conditions, (3) internal mechanisms of water movement, including both liquid and vapor, and (4) continuity relationships between fuel layers with different physical properties. Water budgets require more data and computing power than the older simpler models, although even relatively complex models can be solved rapidly (e.g., <20 seconds for models used in this study).

The DMC was developed for red pine (Pinus resinosa), white pine (Pinus strobes), and jack pine (Pinus banksiana) and is focused on the F layer. It considers variables such as the weight and bulk density of the F layer but does not consider other physical variables that influence flow of water through the F layer (e.g., hydraulic conductivity, specific heat, and porosity) (see Appendix and Keith et al. 2010a, 2010b). The inclusion of these physical properties would enable the model to be calibrated for different F layer forest types.

The DC cannot be unambiguously related to the H layer, mineral soil, or large dead fuels (Turner 1972, Van Wagner 1987). Turner (1972) developed the DC to index soil moisture, but it has been correlated to represent something similar to the H layer (deep, compact duff layers; e.g., Muraro and Lawson 1970). This ambiguity creates problems in designing a well-defined water budget to test the DC and leads to the somewhat unsatisfactory assumption that the

![Figure 5. Dry periods in 2007. a.) Simulation to mimic DMC-M of pine F layer (see text for details). b.) Simulation to mimic DC-M of pine H layer (see text for details).](https://academic.oup.com/forestscience/article-abstract/59/1/78/4583670/64)

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DC corresponds to the H layer. Such an assumption is necessary to maintain continuity requirements of the water budget, which leads directly to the next problem.

The two codes are not coupled and so respond independently to changes in temperature and precipitation. This results in both the underestimation and overestimation of the measured water content, as seen in Figures 3, 4, 6, and 7. The measured moisture content of the F and H layers and the water budget modeling (Keith et al. 2010a, 2010b) show that during the drying phase, the F and H layers have diurnal cycles of moisture in which the F layer loses water by evaporation during the afternoon and gains water (primarily liquid but some vapor) from the H layer during the evening and early morning. There are insignificant amounts of lateral moisture movement in both the F and H layers during drying periods (Keith et al. 2010a, 2010b).

The modification of the water budget processes to simulate the DMC-M and DC-M showed that both codes overestimated moisture in the F and H layers compared with the modified water budget. This finding suggests that the codes are not simply a water budget that lacks the coupling between the F and H layers and/or the evaporation process.

The temporal variability of the empirical moisture data indicates that there are two distinct periods during which

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Figure 6. Spruce site F layer measured gravimetric moisture content (%), predicted DMC-M content (%), and precipitation (mm) during the June–September period for 2007 (a) and 2008 (b).
different processes are controlling the water budget (Keith et al. 2010a, 2010b). The first period involves larger precipitation events, which result in rapid and short vertical and lateral moisture redistribution within the duff layers. It is during this 12- to 24-hour period after larger precipitation events that the spatial variability in the duff layer moisture content is established, particularly in thicker duff layers. This spatial variability in duff moisture content is a result of physical properties in F and H layers, local convergence and divergence in the landscape, precipitation interception, evaporation and the heat budget under or between tree canopies (Miyanishi and Johnson 2002, Raaflaub and Valeo 2008, Keith et al. 2010a, 2010b), and lateral redistribution either through large macropores found in the duff or through small networks of connected macropores (cf. Noguchi et al. 1999, 2001, Sidle et al. 2001, Keith et al. 2010a, 2010b,). In thinner duff layers, there is less evidence that lateral redistribution leads to spatial variability in duff moisture content; this may be due to canopy interception differences and a lack of large macropores (Keith et al. 2010b). The two

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**Figure 7.** Spruce site H layer measured volumetric moisture content ($m^3 m^{-3}$), predicted DC-M ($m^3 m^{-3}$) and precipitation (mm) during the June–September period for 2007 (a) and 2008 (b).
codes responded to precipitation timing well but occasionally overestimated or underestimated the moisture; this was related to issues raised previously.

During the second period when lateral water redistribution ceases, the F and H layer water budget is controlled by vertical fluxes. During this period, the drying of the two layers declines exponentially and diurnal cycles in the moisture content of the F and H layer are evident. The codes predict the exponential decline but, because meteorological data are collected only at solar noon, the diurnal cycles cannot be resolved using the codes. Both model and empirical field evidence suggest that these cycles are caused by evaporative and heat fluxes between the F and H layers. In addition, there appears to be little vertical flow of moisture during drying from the mineral soil to the duff. This result suggests that evaporative fluxes (as opposed to transpiration) may have little direct impact on the mineral soil in regions with a thicker (>10 cm) duff layer.

Finally, the DMC and DC were not designed to predict small spatial and temporal scale variations on the order of meters to hillslopes and <24 hours. The increasing use of prescribed burning and recognition of the role of duff layer removal for vegetation recovery (particularly trees; Miyani-shi and Johnson 2002) means that these smaller scale patterns of duff moisture should be considered in land management practices. On pine hillslopes with thinner duff,
canopy interception of precipitation has been found to be a primary influence of duff moisture content. Hillslope aspect and shape have also been shown to affect temperature and evaporation and thus duff moisture (Miyanishi and Johnson 2002, Raaflaub and Valeo 2008, Keith et al. 2010b). Spruce hillslopes generally have thicker duff layers and, although canopy interception and evaporation are still important factors, the influence of lateral redistribution of moisture during periods of high precipitation is greater.

Conclusion

Although this study considers only pine and spruce subalpine forests, it uses a water budget approach that is applicable for forest surface organic fuels. The measured moisture in the F and H layers differed from that predicted by the DMC and DC. The water budget model was then used to simulate these possible explanations to assess our reasoning. Many of the limitations associated with these models were understood during the development of the FWI system; however, short cuts were necessary at the time (e.g., using a simple temperature-driven empirical model of evaporation instead of the Penman equation) because of computational limitations (McNaughton and Jarvis 1983).

The DMC and DC predictions of moisture do not include coupling of the flow of water (liquid and vapor) between the H and F layers during the daily drying cycle. This coupling, as demonstrated from water budget simulations, appears to cause the smoothing of the response to drying as seen in the measured moisture values but not in the Code-predicted moisture. The patterns of wet and dry periods, hinted at in early measured duff moisture research (e.g., Van Wagner 1970), are integral to understanding how nonlocal and local control (cf. Grayson et al. 1997) produces the seasonal and hillslope patterns. Finally, the hydrologic properties of the duff are not included so the Codes cannot be calibrated for different duff types.

The mechanistic understanding of processes used in formal water budgets is essential as more advanced fire spread models such as the Fire Dynamic Simulator (McGrattan et al. 2007) are developed.

Literature Cited


Mass balance

\[
\frac{d}{dt} \int \int V M dV = \int \int m \cdot n \, d\Gamma + \int \int \omega dV \quad (A.1)
\]

where \( t \) is time (s), \( V \) is Duff layer volume (m\(^3\)), \( M \) is mass (water) accumulation per unit volume (kg m\(^{-3}\)), \( \Gamma \) is Duff layer surface area (m\(^2\)), \( m \) is mass (water) flux vector (kg m\(^{-2}\) s\(^{-1}\)), \( n \) is normal vector at the surface of the duff layer, and \( \omega \) is water sink or source term (kg m\(^{-3}\) s\(^{-1}\)).

Vapor or liquid mass accumulation (\( M \)) equation within the duff layer

\[
M = \phi \sum_{\beta} S_{\beta} \rho_{\beta} \quad (A.2)
\]

where \( \phi \) is porosity, \( \beta \) is phase (vapor, liquid), \( S \) is fraction of pore volume occupied by vapor or liquid (saturation), and \( \rho \) is density (kg m\(^{-3}\)).

Flux (\( m_{\beta} \)) within the duff

\[
m_{\beta} = \rho_{\beta} u_{\beta} = -k \frac{k_{\mu} \rho_{\beta}}{\rho_{\beta}} (\nabla P_{\beta} - \rho_{\beta} g) \quad (A.3)
\]

where \( u \) is Darcy velocity vector for vapor or liquid (m s\(^{-1}\)), \( k \) is absolute permeability (m\(^2\)), \( k_{\mu} \) is relative permeability of duff to the vapor or liquid, \( \mu \) is viscosity of vapor or liquid (Pa s), \( \nabla \) is \((\partial/\partial x, \partial/\partial y, \partial/\partial z)\), \( P_{\beta} \) is fluid pressure (Pa), and \( g \) is the gravitational field vector (m s\(^{-2}\)).

Total water flux (\( m \))

\[
m = \sum_{\beta} X_{\beta} m_{\beta} \quad (A.4)
\]

\[
m_{\text{diff}} = - \phi \tau_{0} \tau_{\beta} \rho_{\beta} d_{\beta} \nabla X_{\beta} \quad (A.5)
\]

where \( \tau_{0} \tau_{\beta} \) is tortuosity for vapor or liquid, \( d \) is the diffusion coefficient (m s\(^{-1}\)) for vapor or liquid, and \( X_{\beta} \) is the vertical mass fraction gradient for a given phase and component:

\[
\tau_{0} \tau_{\beta} = \phi^{1/3} S_{\beta}^{10/3} \quad (A.6)
\]

Effective multiphase diffusion coefficient, \( \Sigma_{\beta} \)

\[
\Sigma_{\beta} = \phi \tau_{0} \tau_{\beta} \rho_{\beta} d_{\beta} \quad (A.7)
\]

Multiphase diffusive flux (\( m_{\text{diff}} \)) through the duff

\[
m_{\text{diff}} = \sum_{\beta} \nabla X_{\beta} - \sum_{\beta} \nabla X_{\alpha} \quad (A.8)
\]

where subscripts \( \beta \) and \( \alpha \) represent the liquid and vapor phases, respectively.

Energy flux across boundaries of duff

\[
\frac{d}{dt} \int \int V Q dV = \int \int q \cdot n d\Gamma + \int \int \omega dV \quad (A.9)
\]

where \( Q \) is energy accumulation term (J m\(^{-3}\)), \( q \) is the energy flux vector (J m\(^{-2}\) s\(^{-1}\)), and \( \omega \) is the energy sink or source term (J m\(^{-3}\)):

\[
Q = (1 - \phi) \rho_{m} C_{m} T + \phi \sum_{\beta} S_{\beta} \rho_{\beta} \omega_{\beta} \quad (A.10)
\]
where $\rho_n$ is density of the duff (kg m$^{-3}$), $C_m$ is specific heat of the duff (J kg$^{-1}$ K$^{-1}$), $T$ is temperature (K), and $u$ is specific internal energy (J kg$^{-1}$).

Energy fluxes ($q$) within the duff layer:

$$ q = -\lambda \nabla T + \sum_{\beta} h_{\beta \beta} m_{\beta} $$  \hspace{1cm} (A.11)

where $\lambda$ is thermal conductivity (W m$^{-1}$ K$^{-1}$) and $h_{\beta \beta}$ is specific enthalpy of a given phase (J kg$^{-1}$). Volume averages

$$ \int_{V_n} M dV = V_n M_n $$  \hspace{1cm} (A.12)

where $V_n$ is volume of an arbitrary cell ($n$) and $M_n$ is average mass accumulated across $V_n$.

Surface integrals

$$ \int_{s_n} \mathbf{m} \cdot \mathbf{n} d\Gamma = \sum_{m} A_{nm} m_{nm} $$  \hspace{1cm} (A.13)

where $m_{nm}$ is mean value of the normal component of the mass flux $\mathbf{m}$ across the surface of the cell ($A_{nm}$) between cell node volumes $V_n$ and $V_m$, and $A_{nm}$ is surface area between cell node volumes $V_n$ and $V_m$. Subscript $nm$ represents calculated average value of parameter or flux at cell interface.

$$ m_{\beta \beta nm} = - k_{nm} \left[ \frac{k_{\beta \beta}}{h_{\beta \beta}} \right] \left[ \frac{P_{\beta n}}{D_{nm}} - \rho_{\beta \beta nm} g_{nm} \right] $$  \hspace{1cm} (A.14)

where $D_{nm}$ is distance between the cell nodes $n$ and $m$ and $g_{nm}$ is gravitational acceleration between cell nodes $n$ and $m$.

Potential evaporation rate (Penman 1948)

$$ E_p = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} E_A $$  \hspace{1cm} (A.15)

where $E_p$ potential evaporation (W m$^{-2}$), $\Delta$ is slope of saturation vapor pressure versus temperature curve (Pa K$^{-1}$), $R_n$ is net radiation flux density (W m$^{-2}$), $\gamma$ is psychrometric constant (Pa K$^{-1}$), and $E_A$ Air drying power (W m$^{-2}$).

**Actual Evaporation Rates**

Duff Moisture Accounting Model (Brutsaert 2005)

$$ \delta = \frac{\theta - \theta_0}{\theta_{\max} - \theta_0} $$  \hspace{1cm} (A.16)

where $\theta$ is moisture content (m$^3$ m$^{-3}$), $\theta_0$ is moisture content when the actual evaporation rate is 0 (m$^3$ m$^{-3}$), and $\theta_{\max}$ is moisture content when the actual evaporation rate equals potential evaporation rate (m$^3$ m$^{-3}$):

$$ E_e = 3.6 \times 10^6 \frac{\delta E_p}{\rho L} $$  \hspace{1cm} (A.17)

where $E_e$ is actual evaporation rate (mm hour$^{-1}$), $\rho$ is water density (kg m$^{-3}$), and $L$ is latent heat of vaporization (J kg$^{-1}$).