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A Conceptual Interpretation of the Drought Code of the Canadian Forest Fire Weather Index System

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Abstract: The Drought Code (DC) was developed as part of the Canadian Forest Fire Weather Index System in the early 1970s to represent a deep column of soil that dries relatively slowly. Unlike most other fire danger indices or codes that operate on gravimetric moisture content and use the logarithmic drying equation to represent diffusion, the DC is based on a model that balances daily precipitation and evaporation. This conceptually simple water balance model was ultimately implemented using a "shortcut" equation that facilitated ledgering by hand but also mixed the water balance model with the abstraction equation, obscuring the logic of the model and concealing two important variables. An alternative interpretation of the DC is presented that returns the algorithm to an equivalent but conceptual form that offers several advantages: The simplicity of the underlying water balance model is retained with fewer variables, constants, and equations. Two key variables, daily depth of water storage and actual evaporation, are exposed. The English system of units is eliminated and two terms associated with precipitation are no longer needed. The reduced model does not include or depend on any soil attributes, confirming that the nature of the "DC equivalent soil" cannot be precisely known. While the "Conceptual Algorithm" presented here makes it easier to interpret and understand the logic of the DC, users may continue to use the equivalent "Implemented Algorithm" operationally if they wish.

Keywords: Canadian Forest Fire Danger Rating System; fuel moisture content; Soil Moisture Index; boreal forest; water balance model; forest floor

1. Introduction

The Fire Weather Index System (FWI) of the Canadian Forest Fire Danger Rating System works well in forested ecosystems where organic soil layers are the primary surface fuels [1]. In North America it is used in boreal forests across Canada, Alaska, and the Lake States of the USA. The FWI comprises three moisture codes and three fire danger indices [2]. The three moisture codes, the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and the Drought Code (DC) feature increasing drying timelags. They independently track the movement of water in soil profiles of increasing depth through a "bookkeeping" system in which today's code is built on yesterday's. The moisture codes rely on the four weather variables, air temperature, relative humidity, wind speed, and precipitation, and consist of underlying semi-physical models of moisture movement finished with abstraction equations that cause fire danger to increase as fuel moisture is depleted. The three moisture codes are then combined with wind to yield three fire danger indices that represent potential spread rate, fuel weight consumed, and frontal fire intensity [2–4].

During development of the FWI there was need for an indicator of steadily increasing drought in slow-drying, deep soil layers [1,2,5]. Drought is a variable factor of the fire environment that changes at the scale of the season but provides important background context in the management of wildland fire. While properties of flaming combustion such as flame length and rate of spread readily respond to the effects of short-term weather events on the moisture content of finely divided fuels, fire attributes such as burn severity, depth of burn, amount of fuel consumed, difficulty of control, and fire effects are better related to moisture trends in large fuels and deeper soils [6,7]. The need for a moisture code with a relatively long drying timelag was filled by adapting a water balance model developed by J.A. Turner in 1966 that tracks the depth of water stored in the soil [8,9]. It is not well known that Turner actually presented two versions of the water balance model, one that he described conceptually in the text of his paper and another that he presented as a mathematical algorithm. The latter is more computationally efficient for hand ledgering in the absence of rainfall and was ultimately implemented in the FWI in 1974 [5]. His "Conceptual Algorithm", on the other hand, has several key advantages over the "Implemented Algorithm" which are argued here. For convenience, the two algorithms are compared in Section 5.

2. Turner's Water Balance Model

The water balance model underlying the DC is somewhat different from most other fire danger rating codes or indices which use the logarithmic drying rate equation to transport moisture through the bulk of a fuel by diffusion [2,10–13]. The DC water balance model similarly features negative exponential drying and a resultant timelag but it operates in units of water storage depth rather than percent gravimetric moisture content. At its simplest, a water balance model is the result of daily increments of precipitation less evaporation at an evaporimeter. The surface of the water is fully exposed to the sun and wind and unlimited evaporation occurs at the potential evaporation rate, E_{pot} (mm; Symbols and units are listed in the Abbreviations section):

$$S = S_0 + P - E_{pot} \tag{1}$$

where S_0 and S (mm) are yesterday's and today's storage depths, P is precipitation (mm), and the elapsed time is one day. Potential evaporation is the atmospheric demand for moisture [14–16] and is not dependent on soil or fuel properties. While this water balance equation does not require any soil, nearly all fire danger rating codes and indices represent some component of the fuel bed. To simulate the presence of a soil, Turner substituted actual evaporation, E_{act} (mm) for E_{pot}. Actual evaporation is experienced by a soil when the potential evaporation rate is impeded by diffusion through the bulk of a soil. Turner scaled E_{act} from E_{pot} following relationships characteristic of negative exponential drying. As Van Wagner [12] explained, the timelag of a negative exponential drying function is fixed by the ratio of water storage to the evaporation rate. Timelag, τ (d), is the time it would take to empty the full storage capacity at the potential evaporation rate, or the time to empty the current storage at the actual evaporation rate:

$$\tau = \frac{S_{max}}{E_{pot}} = \frac{S_0}{E_{act}} \tag{2}$$

Turner's scaling is simply a rearrangement of these relationships in which E_{act} is reduced from E_{pot} proportional to the "fullness" of the soil water reservoir seen in Equation (6). Several points are worth emphasizing here. First, substitution of E_{act} into the water balance equation implies that a soil is now (paradoxically) present at the evaporimeter. However, the lack of any soil parameters in Equations (6) and (7) indicates that the physical features of the soil cannot be precisely known. Its only known attributes are hydrological: its water holding capacity and drying timelag. This point is central to any interpretation of the DC water balance model. It is likely that soil attributes can only be estimated through empirical measurements of drying in known soils. Several soils in Pacific Northwestern and Eastern Canada and Alaska, widely varying in attributes, have been purported to dry similarly to the DC [2,17]. Second, it is reasonable to assume that E_{act} is limited by diffusion through the bulk of the soil. Consequently, the actual evaporation rate is, in effect, equivalent to the internal diffusion rate and could be described either way. Resistance to diffusion or actual evaporation increases with decreasing water storage and, under increasingly drier conditions, less and less water is available for evaporation at the surface of the soil. The scaling is responsible for the drying timelag that is directly comparable to other fire danger rating codes or indices. Similar scalings are seen in hydrological models [18], agricultural systems, e.g., crop coefficients [19], and the Finnish Forest Fire Index [20,21].

At this point it can be appreciated that the basic framework of the water balance model is simple enough to be described in Equations (6) and (7). The rest of this section describes how its inputs are defined and treated. Both Turner's Conceptual and Implemented Algorithms are identical in a maximum storage capacity of $S_{max} = 203$ mm (i.e., 8 inches) and in the estimation of precipitation and potential evaporation from environmental variables. They only differ in the calculation of actual evaporation which is discussed later. Precipitation is corrected for forest canopy interception in Equation (4) where P_{open} is measured daily rainfall at an open weather station (mm). Potential evaporation is estimated in Equation (5) from the air temperature, T_a (°C), adjusted by a monthly base value, $E_{pot,adj}$ (mm) from Table 1. The coefficient, 0.0914, is in units of mm of potential evaporation per °C of air temperature. It was empirically derived from evaporimeter measurements from British Columbia, Canada [9]. The term evaporation is used here rather than evapotranspiration because the water balance equation occurs at an evaporimeter and there is no assumption of transpiration by plants. Yesterday's storage depth, S_0, is now adjusted by P and E_{act} using Equations (6) and (7), and S is abstracted to a new DC value using Equation (8).

3. Discussion

The biggest difference between Turner's Conceptual and Implemented algorithms is the treatment of actual evaporation. In the Implemented Algorithm E_{act} was calculated by a "shortcut" equation conducive to hand computation: E_{pot} was added directly to D_0 in Equation (12). While the equation facilitated ledgering of the DC at a time when bookkeeping was done by hand, the FWI is currently automated by computers and computational efficiency is no longer a concern. Of more importance to the user is an understanding of the logic behind the water balance model. Equation (12) is abstruse for several reasons. The equation mixes the water balance model with the abstraction equation, specifically, E_{pot}, a water balance term in units of millimeters is added directly to the DC, an abstract fire weather index with no units. S and E_{act} are expected in the calculation of D but their contributions are concealed. Separating the terms of Equation (12) into their logical places in the water balance model and the abstraction equation obviates these problems. Last, the approach relies on a conversion factor, a, a scalar between the water balance model in units of storage depth and a parallel system expressed in units of gravimetric moisture content. Both a and the parallel system are not needed in the "Conceptual Algorithm".

A second problem with the "shortcut" equation (Equation (12)) is that it leads to a slightly different result than Equation (8), particularly when soils are near saturation. The problem arises because D is not actually abstracted from S in the Implemented Algorithm. The discrepancy is negligible and may be ignored for the most part, being less than 0.13 units of DC at a reasonably high E_{pot} of 5 mm. If needed, a correction is given in Section 5.

Although the Implemented Algorithm is more computationally efficient on rainless days, it uses more variables, constants, and equations overall. Water storage depth, S, is not an output of the Implemented Algorithm (the output is D) so must be calculated from yesterday's DC at the next daily iteration by Equation (9). Since bookkeeping in the Conceptual Algorithm is done in units of S, neither D_0 nor Equation (9) are needed. Two intermediate equations and variables in the Implemented Algorithm are also unnecessary: water storage depth adjusted for precipitation, S_p, in Equation (10), and the DC adjusted for precipitation, D_p, in Equation (11). Equation (10) is simply the precipitation half of Equation (7). Since the Conceptual Algorithm uses exclusively metric units the conversion factor, b in Equation (10) becomes one and is eliminated. The constant 400 in Equation (8) is asserted to be the the maximum percent gravimetric moisture content held by duff [2,9] but it is less distracting in this interpretation to consider it physically meaningless since it occurs in the abstraction equation and has no bearing at all on water balance or storage.

A last point of discussion concerns the location of the water balance model which is not entirely clear. Correction of rainfall by canopy interception is explicit in Equation (4) suggesting it is located in a forest. However, Turner based E_{pot} (Equation (5)) on evaporimeter measurements from 32 presumably open weather stations in British Columbia, Canada [9]. The algorithm includes no complementary correction of E_{pot} for shading and sheltering by a forest canopy. This imbalance remains an eccentricity of the DC.

4. Conclusions

The Conceptual Algorithm of the DC offers several advantages over the Implemented Algorithm. Unnecessary and confusing parts have been eliminated, leaving the inter-workings of its fewer remaining parts more apparent and the contributions of individual terms better interpretable. All of the variables of Turner's description of the water balance model explicitly appear with their associated units in fewer, more logically organized equations. Fully separating the water balance model from the abstraction equation reveals the current water storage depth and the treatment of drying by actual evaporation. The "bookkeeping" is done in units of S, thus the variable D_0 in the Implemented Algorithm is not needed. Two other intermediate variables associated with rainfall are also unnecessary. Elimination of both the English system of units and a parallel water balance expressed in units of gravimetric moisture content provides consistency and eliminates two conversion factors.

Since the water balance model of the DC does not include any soil parameters its only known attributes are its water storage capacity, $S_{max} = 203$ mm, and its drying timelag. It should not be assumed that this is the water storage capacity of a "DC equivalent soil" which could be considerably shallower (e.g., [17]). The depth, bulk density, fuel weight, and other attributes of such a soil, including the assumption that it is organic, likely can be known only through empirical comparison with drying timelags of known soils.

The Conceptual Algorithm does not change the way that the DC fits into the FWI. Both algorithms give the same answer. It rather provides a cleaner and more logical framework for understanding how the answer is given. While the Conceptual Algorithm can be substituted in all applications where the DC is used, its clarity may best serve in an analytical context (e.g., ground-truthing field measurements of soil moisture [22], remote sensing [23,24], reformulation to fit non-boreal biomes [25], implications for climate change [26]), or as an instructional aid. Users may continue to use the Implemented Algorithm operationally if they wish.

5. Comparison of the Algorithms

The algorithms are compared in this section. To make the comparison easier millimeters are used rather than hundredths of an inch (hundredth) as in Van Wagner and Pickett [27] and Van Wagner [2]. The original S_{max} of 800 hundredths is here 203 mm. The original unit conversion factors $a = 0.5\ \%\,\text{hundredth}^{-1}$ and $b = 3.937\ \text{hundredth}\,\text{mm}^{-1}$ are here equal to $a = 1.97\ \%\,\text{mm}^{-1}$ and $b = 1\ \text{mm}\,\text{mm}^{-1}$.

As mentioned earlier, the Implemented and Conceptual Algorithms better agree if a correction is used for S in Equation (8), the harmonic mean of S and S_0:

$$S_{harmonic} = \frac{2\,S\,S_0}{S_0 + S} \tag{3}$$

but, for the most part, the discrepancy is negligible and can be ignored.

There are several restrictions to the algorithms. Equations (9)–(11) are not used if $P_{open} \leq 2.8$ mm. S may not be greater than 203 mm, the point at which runoff occurs; Let $S = 203$. Nor can S be less than zero, i.e., soil storage cannot be less than empty; Let $S = 0$. If the air temperature is less than

-2.8 °C, let $T_a = -2.8$. E_{pot} may not be less than zero; Let $E_{pot} = 0$. A suggested starting value in the spring is $S_0 = 196$ mm (i.e., a DC of 15) [2].

Both Algorithms

$$P = \begin{cases} 0, & \text{if } P_{open} \leq 2.8 \\ 0.83\ P_{open} - 1.27, & \text{if } P_{open} > 2.8 \end{cases} \tag{4}$$

$$E_{pot} = 0.0914\ (T_a + 2.8) + E_{pot,adj} \tag{5}$$

Table 1. Monthly adjustments to potential evaporation.

Month	$E_{pot,adj}$ (mm)
April	0.229
May	0.965
June	1.47
July	1.63
August	1.27
September	0.610
October	0.102
November–March	−0.406

Conceptual Algorithm

$$E_{act} = E_{pot}\,\frac{S_0}{203} \tag{6}$$

$$S = S_0 + P - E_{act} \tag{7}$$

$$D = 400 \ln \frac{203}{S} \tag{8}$$

Implemented Algorithm

$$S_0 = 203 \exp \frac{-D_0}{400} \tag{9}$$

In the Conceptual Algorithm, S_0 comes from S in Equation (7). Equation (9) is not necessary.

$$S_p = S_0 + P\ b \tag{10}$$

P is treated in Equation (7). S_p and Equation (10) are unnecessary.

$$D_p = 400 \ln \frac{203}{S_p} \tag{11}$$

S_p is unnecessary, therefore D_p and Equation (11) are also unnecessary.

$$D = D_0\ (\text{or } D_p) + E_{pot}\ a \tag{12}$$

Equation (12) simultaneously treats (but conceals) E_{act} and S. It is broken into Equations (6)–(8) in the Conceptual Algorithm.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviations	
DC	Drought Code
DMC	Duff Moisture Code
FFMC	Fine Fuel Moisture Code
FWI	Fire Weather Index System of the Canadian Forest Fire Danger Rating System
Variables	
a	Conversion factor equal to $\frac{400\%}{S_{max}}$. See Section 5.
b	Unit conversion factor. See Section 5.
D	Drought Code (Unitless)
D_0	Drought Code, yesterday's (Unitless)
D_p	Drought Code, corrected for precipitation (Unitless)
E_{act}	Actual evaporation (mm)
E_{pot}	Potential evaporation (mm)
$E_{pot,adj}$	Potential evaporation, monthly adjustment from Table 1 (mm)
P	Precipitation corrected for canopy interception (mm)
P_{open}	Precipitation in the open (mm)
S	Soil water storage (mm)
S_0	Soil water storage, yesterday's (mm)
$S_{harmonic}$	The harmonic mean of S_0 and S (mm). See Section 5.
S_{max}	Maximum water storage (mm)
S_p	Soil water storage, corrected for precipitation (mm)
T_a	Air temperature (°C)

References

1. Stocks, B.J.; Lawson, B.D.; Alexander, M.E.; Van Wagner, C.E.; McAlpine, R.S.; Lynham, T.J.; Dubé, D.E. The Canadian Forest Fire Danger Rating System: An overview. *For. Chron.* **1989**, *65*, 450–457. [CrossRef]
2. Van Wagner, C.E. *Development and Structure of the Canadian Forest Fire Weather Index System*; Forestry Technical Report 35; Canadian Forestry Service: Ottawa, ON, Canada, 1987.
3. Stocks, B.J.; Lawson, B.D.; Alexander, M.E.; Van Wagner, C.E.; McAlpine, R.S.; Lynham, T.J.; Dube, D.E. The Canadian System of Forest Fire Danger Rating. In Proceedings of the Conference on Bushfire Modelling and Fire Danger Rating Systems, CSIRO, Canberra, Australia, 11–12 July 1988; pp. 9–18.
4. Wotton, B.M. Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. *Environ. Ecol. Stat.* **2008**, *16*, 107–131. [CrossRef]
5. Van Wagner, C.E. *Structure of the Canadian Forest Fire Weather Index*; Technical Report; Departmental Publication 1333; Canadian Forestry Service, Petawawa Forest Experiment Station: Chalk River, ON, Canada, 1974.

6. Miyanishi, K. Duff Consumption. In *Forest Fires: Behavior and Ecological Effects*, 1st ed.; Johnson, E.A., Miyanishi, K., Eds.; Academic Press: San Diego, CA, USA, 2001; pp. 437–475.
7. Ryan, K.C. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. *Silva Fenn.* **2002**, *36*, 548. [CrossRef]
8. Turner, J.A. *The Stored Moisture Index: A Guide to Slash Burning*; Technical Report; British Columbia Forest Service, Protection Division: Victoria, BC, Canada, 1966.
9. Turner, J.A. *The Drought Code Component of the Canadian Forest Fire Behavior System*; Technical Report; Publication No. 1316; Environment Canada, Canadian Forestry Service: Ottawa, ON, Canada, 1972.
10. Nelson, R.M. *Some Factors Affecting the Moisture Timelags of Woody Materials*; Technical Report; Research Paper SE-44; U.S. Forest Service, Southeastern Forest Experiment Station: Asheville, NC, USA, 1969.
11. Van Wagner, C.E. A laboratory study of weather effects on the drying rate of jack pine litter. *Can. J. For. Res.* **1979**, *9*, 267–275. [CrossRef]
12. Van Wagner, C.E. *Drought, Timelag, and Fire Danger Rating*; Eighth Conference on Fire and Forest Meteorology; Society of American Foresters: Detroit, MI, USA, 1985; pp. 178–185.
13. Byram, G.M.; Nelson, R.M. *An Analysis of the Drying Process in Forest Fuel Material*; Technical Report; e-General Technical Report SRS-200; U.S. Forest Service, Southern Research Station: Asheville, NC, USA, 2015.
14. Nelson, R.M. Water Relations of Forest Fuels. In *Forest Fires: Behavior and Ecological Effects*, 1st ed.; Johnson, E.A., Miyanishi, K., Eds.; Academic Press: San Diego, CA, USA, 2001; pp. 79–149.
15. McMahon, T.A.; Peel, M.C.; Lowe, L.; Srikanthan, R.; McVicar, T.R. Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: A pragmatic synthesis. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 1331–1363. [CrossRef]
16. Hobbins, M.; Huntington, J. Evapotranspiration and evaporative demand. In *Handbook of Applied Hydrology*, 2nd ed.; McGraw-Hill Publishing: New York, NY, USA, 2016; pp. 42.1–42.18.
17. Miller, E.; Wilmore, B. Evaluating the Drought Code Using In Situ Drying Timelags of Feathermoss Duff in Interior Alaska. *Fire*, under review.
18. Johnson, E.; Keith, D.; Martin, Y. Comparing measured duff moisture with a water budget model and the duff and drought codes of the Canadian Fire Weather Index. *For. Sci.* **2013**, *59*, 78–92. [CrossRef]
19. Hanks, R.J.; Ashcroft, G.L. *Applied Soil Physics: Soil Water and Temperature Applications*; OCLC: 5029519; Springer: Berlin, Germany; New York, NY, USA, 1980.
20. Heikinhemo, M.; Venäläinen, A.; Tourula, T. A soil moisture index for the assessment of forest fire risk in the boreal zone. In Proceedings of the International Symposium on Applied Agrometeorology and Agroclimatology, Volos, Greece, 24–26 April 1996; Dalezios, N., Ed.; European Commission: Volos, Greece, 1998; pp. 549–555.
21. Venäläinen, A.; Heikinheimo, M. The Finnish Forest Fire Index Calculation System. In *Early Warning Systems for Natural Disaster Reduction*; Zschau, J., Kuppers, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2003; pp. 645–647._88. [CrossRef]
22. Lawson, B.D.; Dalrymple, G.N. *Ground-Truthing the Drought Code: Field Verification of Overwinter Recharge of Forest Floor Moisture, with Errata (2012)*; Technical Report; FRDA Report 268; Canada/British Columbia Partnership Agreement On Forest Resource Developement: FRDA II; Forestry Canada, Pacific Forestry Centre: Victoria, BC, Canada, 1996.
23. Bourgeau-Chavez, L.; Kasischke, E.S.; Rutherford, M.D. Evaluation of ERS SAR data for prediction of fire danger in a boreal region. *Int. J. Wildland Fire* **1999**, *9*, 183–194. [CrossRef]
24. Bourgeau-Chavez, L.L.; Garwood, G.; Riordan, K.; Cella, B.; Alden, S.; Kwart, M.; Murphy, K. Improving the prediction of wildfire potential in boreal Alaska with satellite imaging radar. *Polar Rec.* **2007**, *43*, 321–330. [CrossRef]
25. Yang, Y.; Uddstrom, M.; Pearce, H.; Revell, M. Reformulation of the Drought Code in the Canadian Fire Weather Index System Implemented in New Zealand. *J. Appl. Meteorol. Climatol.* **2015**, *54*, 1523–1537. [CrossRef]

26. Flannigan, M.D.; Wotton, B.M.; Marshall, G.A.; de Groot, W.J.; Johnston, J.; Jurko, N.; Cantin, A.S. Fuel moisture sensitivity to temperature and precipitation: Climate change implications. *Clim. Chang.* **2016**, *134*, 59–71. [CrossRef]
27. Van Wagner, C.E.; Pickett, T.L. *Equations and FORTRAN Program for the Canadian Forest Fire Weather Index System*; Technical Report; Forestry Technical Report 33; Canadian Forest Service: Ottawa, ON, Canada, 1985.