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A mechanistic live fuel moisture model

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Abstract

Wildland fires are a common global disturbance and many of these fires burn through mixtures of living and dead vegetation. Live fuels are unique because they regulate biomass and water content actively through processes such as photosynthesis or transpiration. The main goal of these processes is to maintain the growth and maintenance demands of the plants while minimising water loss. Historically, live fuel dynamics were assumed to be only driven by evaporative or drying processes and little attention was paid to the interplay between carbon and water dynamics. Here we present a mechanistic model of live fuel moisture (LFM) which is a critical component of live fuel flammability. The model decouples LFM into physical and chemical metrics that are easy to. Each metric serves as a proxy for important components of the seasonal water and carbon cycle or to capture inter-species variations in physical properties. We evaluate this model using field measurements of physical and chemical characteristics for a Douglas Fir (*Pseudotsuga menziesii*), a common intermountain US tree species that commonly burns in crown fires. This simple, mechanistic model was effective at characterising the seasonal variations in LFM across both new and old foliage as a simple function of specific leaf area, surface-area-to-volume ratio, relative water content and a species-specific scalar ($r2=0.995$, $p < 0.05$). Finally, we suggest how this decoupled model can be used to more appropriately parameterize a 3-dimensional computational fluid dynamics-based fire behaviour model to represent an appropriate live fuel moisture as the combined effects of biomass and moisture variations on canopy flammability.

1. Introduction

Wildland fires are a common global disturbance and many of these fires burn through mixtures of living and dead vegetation. While there have been extensive studies exploring the factors that control dead fuel flammability, there have been considerably fewer studies that focus on live fuels. In part, this is due to the difficulty of controlling live fuel characteristics in the lab and considerable variation both seasonally and spatially of those characteristics in the field. These studies are further complicated by historical assumptions that attempt to link live fuel flammability variations to indicators of drought but many studies have found that drought indicators alone are insufficient to capture seasonal live fuel moisture variations (Pellizzaro et al., 2007,, Ruffault et al., 2018). While this is partially accurate, live fuel flammability variations are driven by several interacting factors such as changes in absolute moisture content, variations in needle biomass and structural differences in physical factors such as their surface-area-to-volume ratio. A more complete, mechanistic model of the drivers that influence live fuel moisture variations is needed (Pellizzaro et al., 2007).

2. Methods

We collected new and old live foliar samples bi-weekly from Douglas Fir for the 2021 growing seasons (Apr to October). For each sample we measured live fuel moisture content by weighing samples fresh, drying in a 95 degrees Celsius oven for at least 48 hours and re-weighing samples after drying. After initial fresh weights were taken, a sub-sample of the bulk foliar sample was separated to determine density, surface-area-to-volume ratio and leaf mass area. Foliar volume using an Ohaus density kit on a high precision balance and those samples were retained and dried to compute density. Surface area was measured by scanning the planar surface area and computing the planar surface area using ImageJ. Total surface area was assumed to be 2 time the planar area.

3. The mechanistic live fuel moisture model

We developed and tested a simple, mechanistic model of live fuel moisture. The model decouples factors that are known to influence season variations in live fuel moisture content by varying either their water status / hydration or their dry weight. The model was defined as follows:

$$Live\ Fuel\ Moisture\ (\%\ dry\ wt) = \frac{SLA*RWC*\kappa}{SAV} \qquad \text{Equation 1}$$

SLA is the Specific Leaf Area on a dry weight basis ($m^2\ kg^{-1}$), RWC is the Relative Water Content or a metric of the amount of water in the particle compared to how much water the particle can hold at saturation, *k* is a scalar that represents the amount of water a fuel particle can contain relative to its volume (kg H_20 m-3), SAV is the surface-area-to-volume (SAV) ratio of the particle (m^{-1}). The scalar is a measure of the amount of water a particle can hold relative to its volume and should be species specific but could also be influenced by particle elasticity. When combined, these individual metrics of foliar physical and chemical properties will yield an appropriate metric of live fuel moisture in percent of dry weight.

$$\frac{LFM}{100} = \frac{SLA*RWC*k}{SAV} = \frac{\frac{m^2}{g_{Dry\ Matter}} \times \frac{g_{H_2O}}{g_{H20Sat}} \times \frac{g_{H_2OSat}}{m^3}}{\frac{m^2}{m3}} = \frac{g_{H_2O}}{g_{Dry\ Matter}} \qquad \text{Equation 2}$$

Equation 2 shows that the dimensional analysis of the model will yield a metric with the same units as live fuel moisture content in grams of water per unit gram of dry matter / weight. *k* values were computed from measurements and averaged across needle ages.

4. Results

Seasonal variations in live fuel moisture were most pronounced when comparing new and old growth. During green-up, live fuel moisture contents were over 300% for new foliage, while previous year's foliage had moisture contents near 100% (Figure 1). On average, new foliage moisture content was significantly higher than old foliage moisture content (Figure 2). New foliage had a very low foliar density and very high relative water content while old foliage had a higher density and lower relative water content. Density variations were strongly related to live fuel moisture content variations (Figure 3). Final model predictions showed strong agreement between modelled and predicted live fuel moisture content (rho=0.984, $p < 0.05$) (Figure 4). Mean k values were 736.98 kg $H_20\ m^{-3}$ for new growth and 560.17 kg $H_20\ m^{-3}$. Assuming k as fixed for needle ages, we computed the live fuel moisture content using Equation 1 and compared to the final measured live fuel moistures. The model accurately predicted live fuel moisture content $r^2 = 0.995$ across the range of new and old foliage.

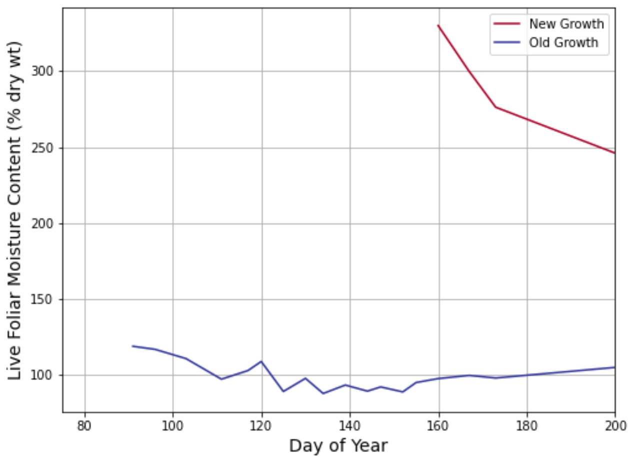

Figure 1 - Seasonal variations in live fuel moisture over the 2021 growing season. New foliage moisture content is shown in Red and previous year's growth in Blue. New growth moisture content was nearly 3 times higher than previous year's growth. Old growth showed a pronounced 'dip' during spring, consistent with other species.

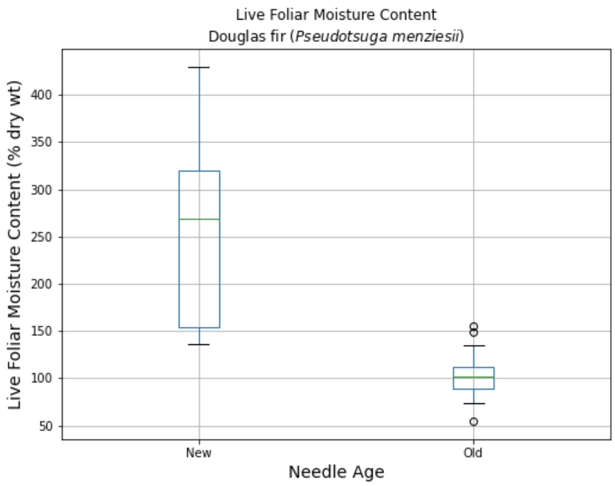

Figure 2 - Difference in live fuel moisture between current year (New) and previous year's growth (Old) for the 2021 growing season of Douglas fir.

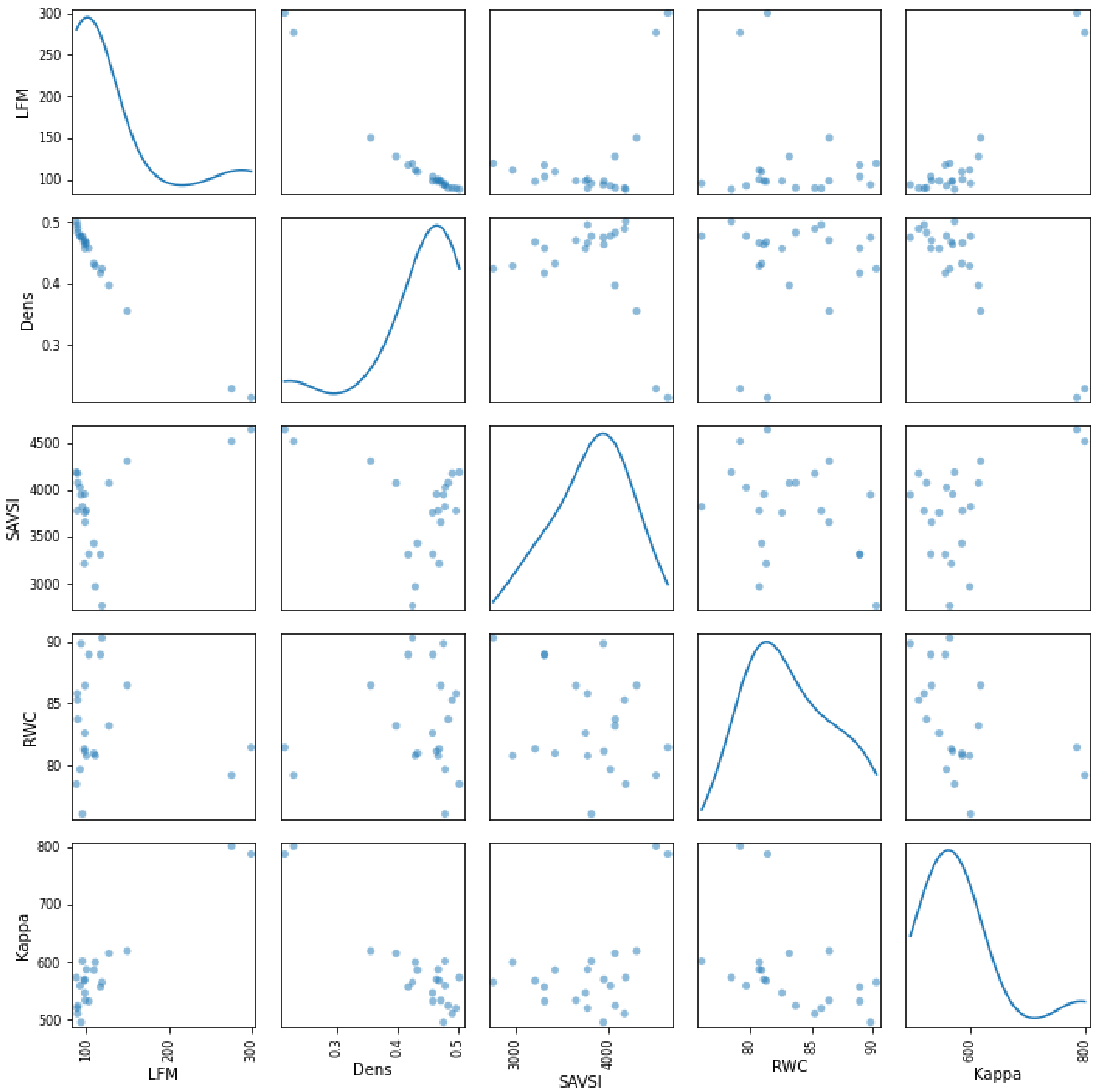

Figure 3 – Cross-scatter plots of input variables to mechanistic live fuel moisture model. LFM is strongly related to density variations and other variables have direct relationships with Live Fuel Moisture (LFM).

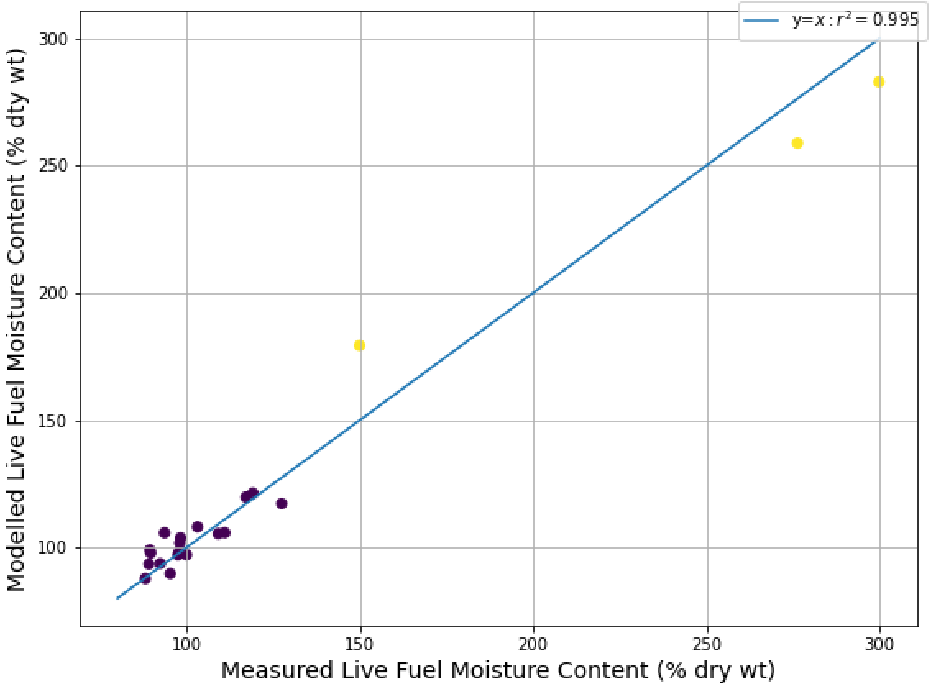

Figure 4 – Preliminary model predictions of live fuel moisture as a function of specific leaf area, relative water content and surface-area-to-volume ratio using a fixed k parameter for new and old foliage.

5. Discussion

This model is the first of its kind to allow the decomposition of live fuel moisture content into components that are easily measured in the field and that allow the decomposition of LFM into components that are important for fire behaviour models. SAV is a critical input to most 2-d and 3-d fire behaviour models because it is primary driver in heat transfer through both radiation and convection. Further, SLA and SAV combine to yield the particle density, which is another very important physical property for heat transfer and subsequent fire behaviour modelling. Finally, RWC is the preferred metric to measure the water status of plants and it dominates plant physiology literature. For example, RWC is strongly linked to soil water potential in Douglas Fir (Barnard et al., 2011) and both metrics correlate well with periods of water stress. Collectively, these variables all yield a framework for better understanding live fuel moisture. As fires grow larger and more intense, understanding the factors that drive live fuel flammability and contribution to overall fire intensity is critical. This mechanistic model of live fuel moisture is one step towards that goal.

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