A MODEL FOR PREDICTING FIRE-INDUCED TREE STEM MORTALITY

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I. ABSTRACT

A deterministic model for predicting cambial tissue necrosis and resulting stem mortality has been proposed. The model accounts for moisture- and temperature-dependent thermophysical properties, desiccation, bark swelling (where appropriate), and charring, as well as species dependent thermal tolerance properties. The tissue necrosis submodel proposes that thermal impairment of tissues or mortality in populations of cells may be described by a rate equation which simulates the rate of decline in tissue viability (*i.e.*, tissue impairment) as being proportional to current viability. The rate parameter is both species- and temperaturedependent. Since tissue temperature varies with time as trees are heated in fires, the rate parameter is thus time-dependent. The combined model produces cambial tissue necrosis predictions in a tree stem as a function of heating rate, heating time, tree species, and stem diameter. The model has the advantage of physical realism, and the potential for extension to other species and stem diameters.

The linked model is presented, and model accuracy is evaluated by comparison with experimental measurements in two hardwood and two softwood species: red maple (*Acer rubrum*), chestnut oak (*Quercus prinus*), ponderosa pine (*Pinus ponderosa*), and Douglas-fir (*Pseudotsuga menziesii*).

II. DISCUSSION

As stated previously, stem survival/mortality is a binary phenomenon since absolute depth-of-kill becomes irrelevant for scenarios where thermal damage penetrates deeper than the vascular cambium. Red maple trees of diameter and bark thickness ranging, respectively, from 4.1 to 15.0 cm and 0.16 to 0.70 cm were heated and the response measured. Comparison between measurements and

predictions indicate that stem survival or mortality is correctly predicted in 15 of the 20 tests. If the variation in depth-of-kill experimental measurements is accounted for (*i.e.*, measured depthof-kills which straddle the cambial radial location), there are perhaps 18 of 20 correct predictions of survival or mortality for the red maple. The data indicate that for this species and heating scenario the coupled stem heating and tissue necrosis model predicts stem mortality accurately in more than 75% of the cases. This is nearly as good as the results of the empirical model presented by Ryan and Reinhardt (1988).

The most rigorous test of the coupled stem heating/tissue necrosis model accuracy is the



Fig. 1. Comparison between predicted and measured depth-of-kill for red maple (*Acer ru-brum*).

comparison between predicted and experimentally measured kill depth. Figure 1 shows the predicted (absolute) kill depth for red maple versus measured kill depth. Perfect accuracy in model predictions would be reflected by the predicted kill depth (PKD) matching the measured kill depth (MKD), *i.e.*, all data lying on the PKD = MKD line. Included in the figure are two linear regressions. The first regression includes all predicted/measured kill depth data. The second regression excludes data for which predicted kill depth reached the stem centerline, which are shown in filled symbols. Agreement between model prediction and these experimental data may be compromised by one or more of the following: *i*) Initial temperatures measured by a single thermocouple near the stem surface for two of these cases were abnormally high ($\geq 30^{\circ}$ C), probably due to stem exposure to solar irradiation prior to the test burns. The temperatures throughout each stem were initialized with this single measured temperature, which was probably not representative of initial temperatures on the stem interior. *ii*) Two of the outlier data were for small (juvenile) stems, with bark thicknesses of 2 mm or less. As reported by Jones et al. (2004), juvenile stems exhibit different moisture profiles than mature stems, and this is more difficult to generalize. Further, the bark for such juvenile stems is much thinner than for more mature stems (< 2 mm). Thus, errors made in characterizing the bark thickness and its moisture content (which represents the primary resistance to penetration of energy to the cambium) in thin-bark stems may result in large errors in predicted depth-of-kill. This was confirmed by parametric model simulations wherein bark thickness for the juvenile stems were increased by 0.5 mm, resulting in significantly lower predicted depth-of-kill. iii) As will be demonstrated in a later section, the V = 0.5 criterion defining depth-of-kill may or may not be appropriate particularly for smaller stems where the temperature rises more uniformly under heating conditions. The sensitivity of this arbitrarily selected kill depth criterion was assessed by varying the V = 0.5 tissue necrosis threshold by 50%, which resulted in quite different predictions for kill depth particularly for small stems.

Both linear regressions shown in Fig. 2 exhibit zero intercept with reasonable accuracy. However, the slope for the regression should be unity. The

data and linear regressions reveal that, in general, the model over-predicts depth-of-kill (as seen by slope greater than unity) for the red maple, particularly at higher kill depth. As was reported previously, the stem heat transfer model is quite sensitive to a number of model inputs, with bark thermal conductivity and moisture content exercising a particularly strong influence on the predicted thermal transport (Jones et al. 2004). The error in predicted absolute depth-of-kill may be the result of inappropriate modeling of bark structure, uncertainty in thermophysical properties, inaccurate assumptions of initial temperature profiles, and/or assumed moisture distribution in the stem. Red maple exhibits thinner bark than either the chestnut oak or Douglas fir studied, suggesting that accuracy of model inputs is more critical for thin-bark species.

Chestnut Oak

As indicated in the description of experimental procedure, the chestnut oak experimental results were obtained in a similar manner to those of red maple (Dickinson *et al.* 2004). From a stem survival/mortality perspective, we found that simulations of chestnut oak heating experiments yielded 17 of 21 correct predictions of cambial death based on the average normalized measured depth-of-kill (measured and predicted kill depth on the same size of unity normalized depth-of-kill). The two cases for which measured depth-of-kill was zero (Experiments 15 and 18) reflect the fact that the TTC stain reveals nothing if the depth-of-kill does not reach the living inner bark layer.

A comparison between predicted and measured absolute depth-of-kill is shown in Fig. 3. Again, perfect accuracy between model prediction and measured data would be indicated by experimental data lying on the PKD = MKD line. Linear regressions of the data are also included in the figure. As was done for the red maple, the two regressions are i) for all prediction data, and *ii*) for data excluding the cases where predictions reached the stem centerline (again shown as filled symbols). These three outliers are juvenile stems, for which predictions may be compromised for the reasons explained previously. The calculated slope in both linear regressions is not radically different from unity. Figure 4 reveals that the coupled thermal transport/tissue necrosis

model predicts absolute depth-of-kill with better accuracy for chestnut oak than was observed in the red maple data. Absolute depth-of-kill is predicted to within the TTC stain test reproducibility indicated by the error bars in 11 of 21 cases for the chestnut oak.



Fig. 3. Comparison between predicted and measured depth-of-kill for chestnut oak (*Quercus prinus*).

Ponderosa Pine

Comparisons between experiment and simulations of Ponderosa Pine indicate that the final cambial viability is slightly over-predicted or in other words that cambial temperatures are under-predicted suggesting that the discrepancy between predicted and measured cambial viability may be due to the thermal transport model, and that the tissue necrosis model will yield correct simulations of tissue impairment if the temperature history is correctly predicted. The prediction of stem survival/mortality for the eleven ponderosa pine experiments reveals that for 8 of the 11 ponderosa pine cases, the model's predictions of tree survival/mortality match those based on measured cambial temperature histories.

Douglas-Fir

Following the same coupled model evaluation approach as that applied to ponderosa pine in the

foregoing section, the Douglas-fir data reported by Jones et al. (2004) were used to explore the model's predictive accuracy for this species. As expected, cambial viability drops due to thermal damage as the temperature rises. Predictions of cambial viability based on predicted cambial temperatures (using the two different incident flux series as input) agree closely with some predictions of viability determined from measured cambial temperatures. As expected from the temperature dependence of the tissue necrosis model, under-predictions in cambial temperature by the stem heating model in result in overpredictions of cambial viability. For the heating intensity and durations of these tests, cambial viability never reaches V = 0.5, arbitrarily defined here as the threshold for cambium necrosis. It is interesting to note that even for these heating scenarios which resulted in relatively low temperatures (peak cambial temperature in the four cases is approximately 45°C-well below the 60°C threshold traditionally accepted for thermal tissue damage), the rate-dependent tissue necrosis model predicts thermal damage, indicated by a loss in tissue viability (V < 1). For these low-intensity, longer duration heating scenarios, however, it is apparent that the choice of particular threshold viability for tissue necrosis may have a large effect on necrosis predictions.

Based on comparison with the data presented in the foregoing sections, it may be stated that the model correctly predicts stem survival/mortality for approximately 75% of the cases explored here. Inaccuracy in the combined models comes from three sources: uncertainty in the experimental measurement of model input data, error and approximation in the stem heating model, and error and approximation in the tissue necrosis model. Trees are composed of anisotropic, non-homogeneous materials for which physical properties are poorly understood. Even the geometry of the tree stem poses difficulty for measurements; the insulating bark layer can have large variations in thickness. The fire that is heating the stem is almost always highly turbulent and variable in intensity. Error and approximation in the stem heating model have been discussed in detail by Jones et al. (2004), and limited parametric studies as part of this work have revealed sensitivity of kill depth

predictions to thermal transport model inputs. The errors associated with the stem heating model, tissue necrosis model, and experimental measurement can be cumulative or multiplicative. However, the data suggest that even with the uncertainty inherent in the process, the linked models have the ability to correctly predict cambial tissue necrosis the majority of the time.

III. CONCLUSIONS

The stem heating model previously outlined by Jones et al. (2004) has been linked to the tissue necrosis model of Dickinson et al. (2004). The resulting model makes it possible to predict the decline in cambial tissue viability at any location in the stem based on an imposed time-varying heat flux at the exterior surface of the stem. This model is unique from currently used tree mortality prediction tools in that it has been developed primarily from a physics basis rather than empirical basis. One of the limitations of such as model is that it requires physical parameters for the species of interest (i.e., thermal conductivity, moisture distribution, density, mortality rate parameters, etc.). There is a paucity of such data. Experimental data from red maple, chestnut oak, Douglas-fir, and ponderosa pine were used to evaluate model performance. In its current form the model is onedimensional and therefore provides a local estimate of tissue survival/mortality. If the model is to be used to estimate whole tree survival or mortality it must either be applied at many discrete locations around the stem or simulate the location with the lowest heat flux and subsequent injury, implying that all other peripheral locations will sustain damage. The results of the linked model presented herein indicate a better than 75% success rate in predicting local cambial mortality, on par with previously published empirical models. The results of this work suggest that with more accurate data input to the thermal transport model, the linked model predictions may be further improved. If indeed a deterministic model like that presented here can provide tree mortality estimates with at least as much accuracy as empirically based approaches it opens the door to the possibility of developing a comprehensive tree and stand fire-induced mortality prediction system that can be applied across a wide variety of species. **IV. REFERENCES**

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Bret Butler works in the Fire Behavior Research Work Unit at the Rocky Mountain Research Station's Intermountain Fire Sciences Laboratory in Missoula, MT. His research focuses on fundamental heat and combustion processes in wildland fire. Applications for his research include fire behavior models, links between fire behavior and effects, and firefighter safety.

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Matthew Dickinson is a Research Ecologist with the USFS Northeastern Research Station. Current research interests focus on physical and ecological processes that determine fuel and fire dynamics on Appalachian landscapes, how trees are killed in fires, and how small mammals are affected by smoke and heat. He joined the USFS in 2001 after 4-years of postdoctoral research and teaching at the University of Calgary where he studied fire extinction in boreal fuels and vascular cambium thermal tolerance. His doctorate is from Florida State University where he studied tree regeneration after logging and natural tree fall in a tropical forest in Mexico.