A Model for the Consumption of Forest Duff by Smoldering Combustion

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I'd do Anything!!
Duff
BEER
HOMEYWEAR

Forest Duff

A cross-section of forest soil.

Forest soils are composed of several distinct layers, or *horizons*:

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The fermentation and humus horizons together constitute what is known as the "duff layer."

Forest Fires and Duff Consumption

Close-up of smoldering duff.

Lateral propagation of smoldering front.

- Duff is composed mostly of organic material and may therefore burn.

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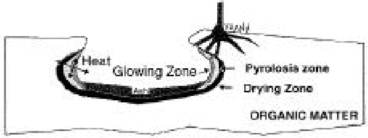

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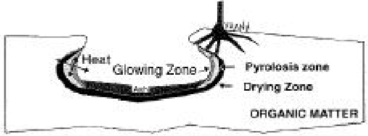

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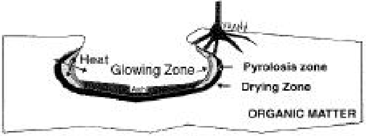

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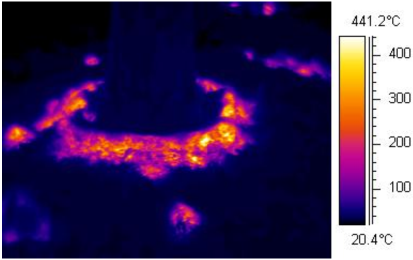
- Duff smolders down to the mineral soil resulting in an outwardly propagating smoldering perimeter.

Ecological Impacts

In regions in which fire suppression has long been practiced, duff that would otherwise be removed by historically frequent, low intensity fires, is allowed to accumulate in thick layers over many years.



Thermal image of duff smoldering at the base of a tree stem.

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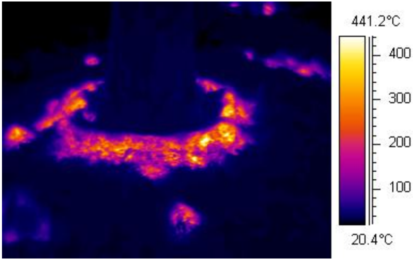

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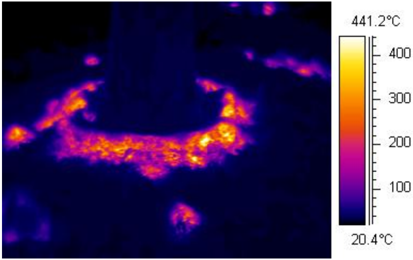

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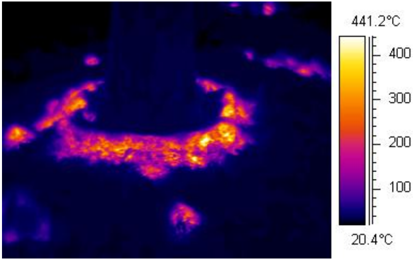

Thermal image of duff smoldering at the base of a tree stem.

Accumulated duff

- affects the propagation of tree and plant species.
- interferes with nutrient cycles.
- if ignited, smolders at the base of trees for several hours or days, leading to tree mortality and the heating of mineral soil to temperatures lethal to soil organisms.

Prescribed Burning (Benefits)

Duff accumulations profoundly impact forest ecology and health. As a result, much effort has been devoted to reintroducing fire to fire suppressed regions by means of prescribed burning. A prescribed burn is a controlled, closely monitored, intentional fire disturbance. The benefits of prescribed burning include

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- exposing mineral soil upon which seedlings may establish.
- making available nutrients in the duff to other organisms.

Prescribed Burning (Hazards)

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- excessive tree mortality due to smoldering duff at the base of tree stems.
- mineral soil erosion as a result of too much duff being removed.
- large quantities of noxious smoke produced by smoldering duff.

Necessity of General Duff Consumption Models

A general spatial model of duff consumption model would allow foresters and ecologists to estimate

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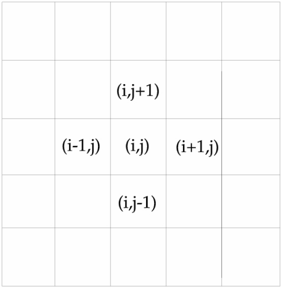
Unfortunately, there are few, if any, general duff consumption models. Models of smoldering combustion often apply to a narrow range of materials and can be difficult to use. Most models of duff consumption are specific to a particular site or duff type.

Model Input

The model requires the following parameters estimated from field samples:

- Mean gravimetric moisture content.
- Mean organic bulk density.
- Mean inorganic content.
- Mean duff thickness.
- Coefficients for duff type (four parameters).

Model Choice



Cell (i, j) and its four nearest neighbors.

- The fuel bed is modeled by a two-dimensional lattice of "cells."

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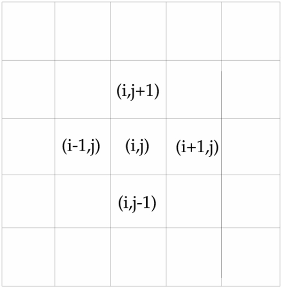

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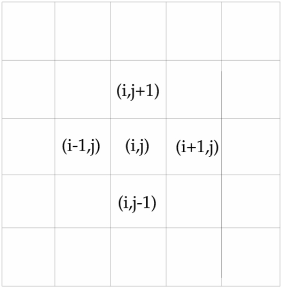

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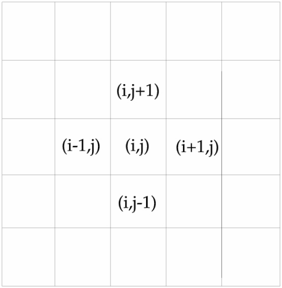

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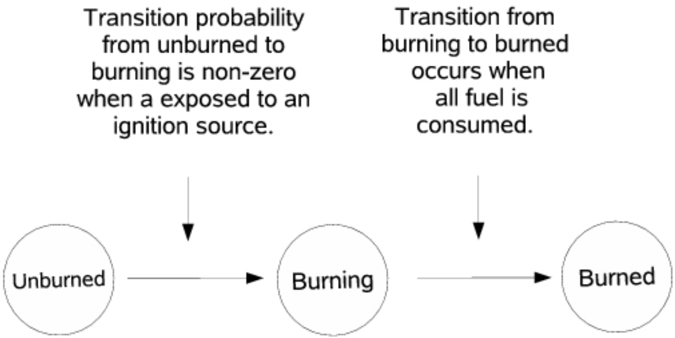
- Associated with each cell are duff conditions and a combustion stage.
- The state of each cell is updated in discrete time using conditions of neighboring cells and itself.

Combustion Stage Dynamics

Due to the complexity of combustion chemistry, the combustion process is modeled stochastically. The stage of combustion for each cell is illustrated by the figure below. The transition probability is determined by duff type and duff conditions of the cell.



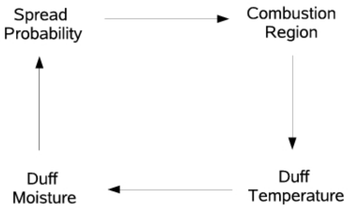
Heat and Moisture Dynamics

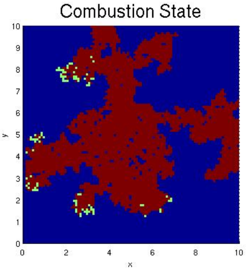
The model makes use of discretized versions of the following equations of simultaneous heat and moisture transport in soil to update duff moisture and temperature for each cell on the lattice:

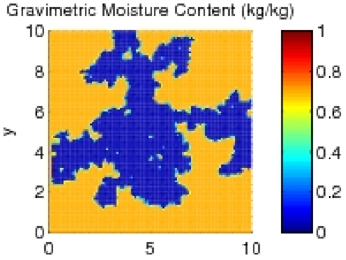
$$C\frac{\partial T}{\partial t} - Hd_w\frac{\partial \theta}{\partial t} = \nabla \cdot (K\nabla T) - \kappa_c C(T - T_a)$$

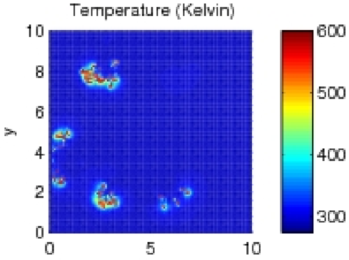
$$d_w\frac{\partial \theta}{\partial t} = -\nabla \cdot \left(\frac{V}{1 - \frac{p}{P_a}}\nabla p\right).$$

Overall Model Dynamics



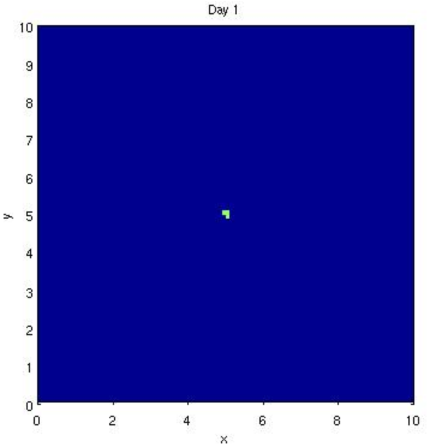






Model Behavior (Spatial Patterns)

Center Ignition with Dry Duff



Unburned Burning Burned

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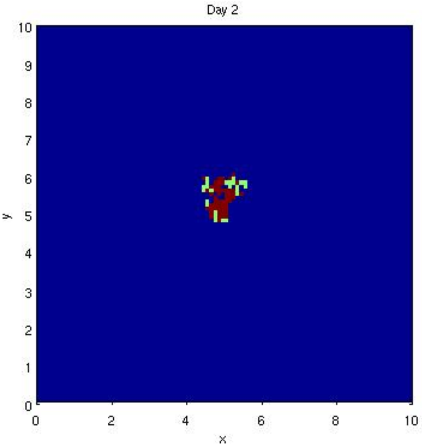

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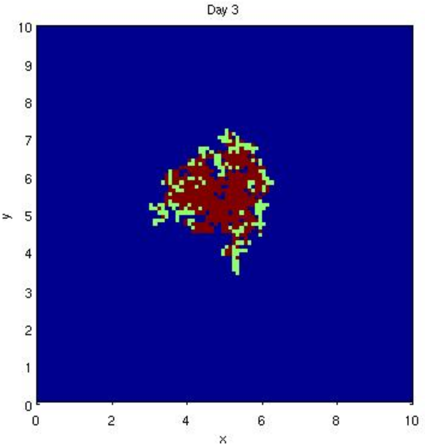

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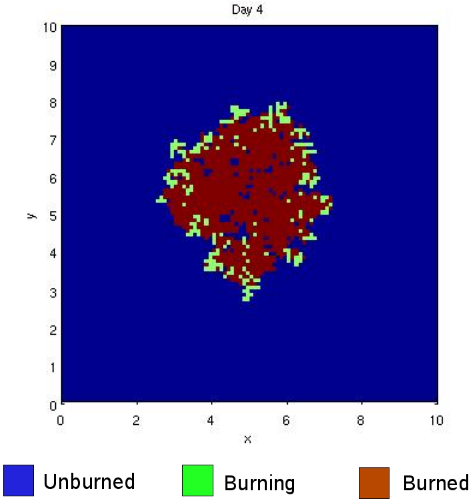

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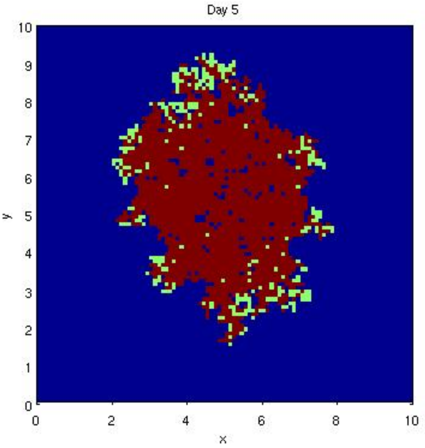

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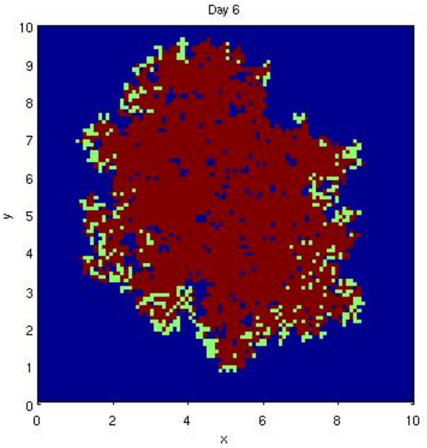

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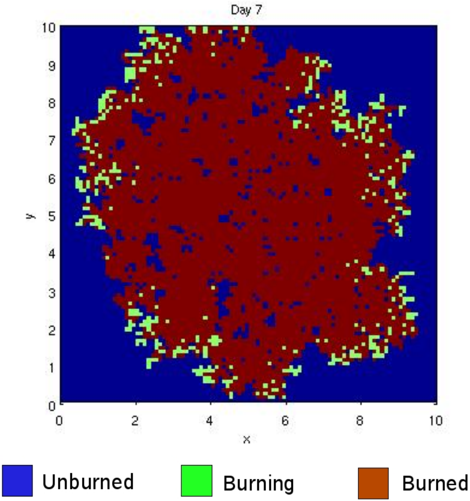

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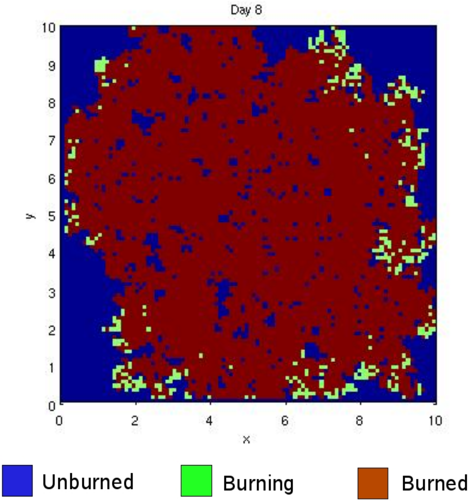

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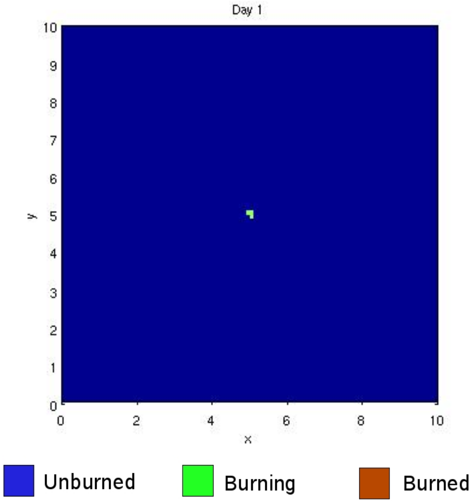

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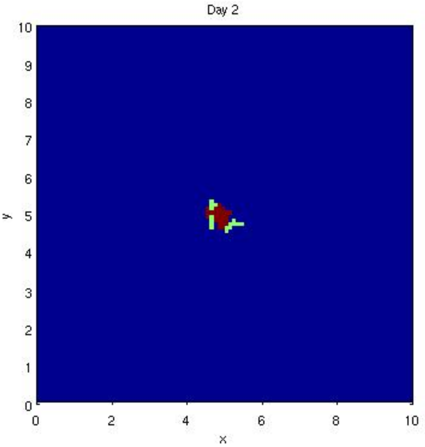

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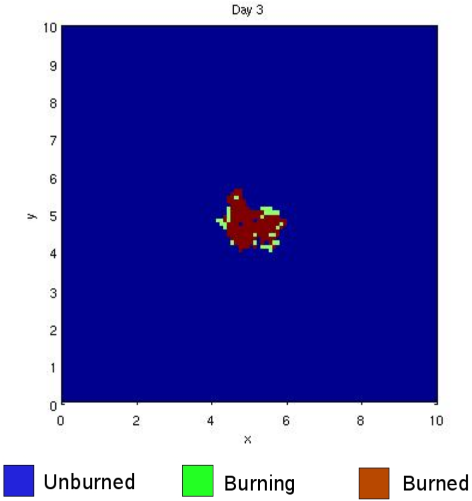

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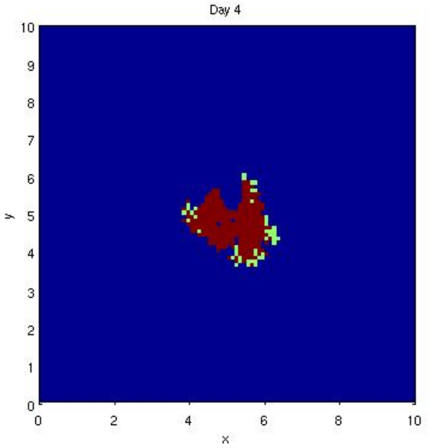

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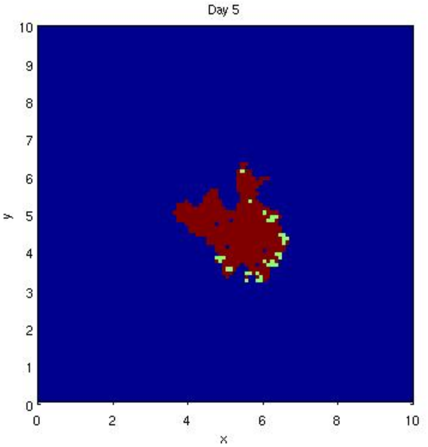

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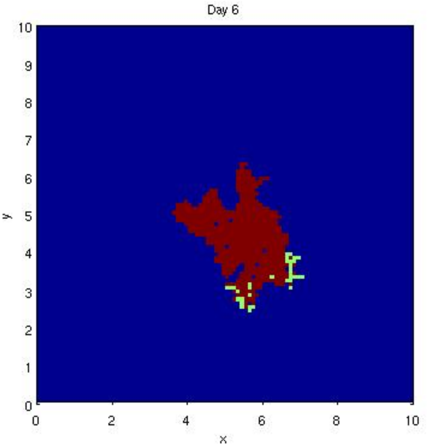

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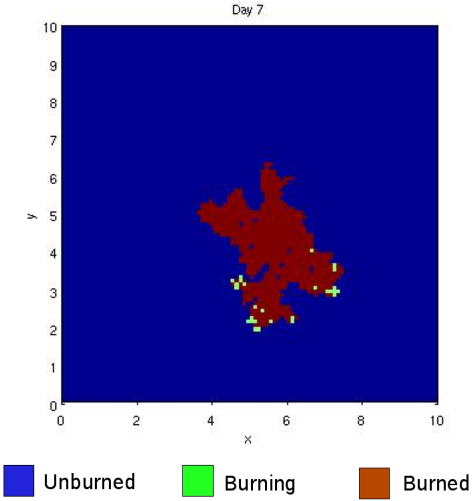

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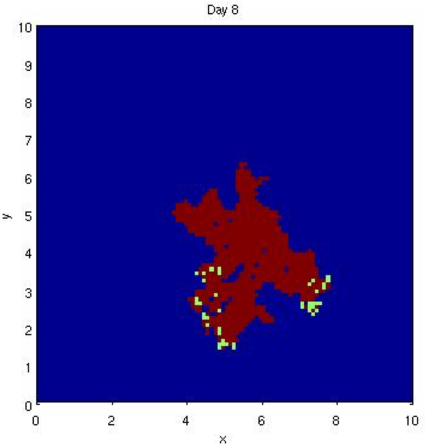

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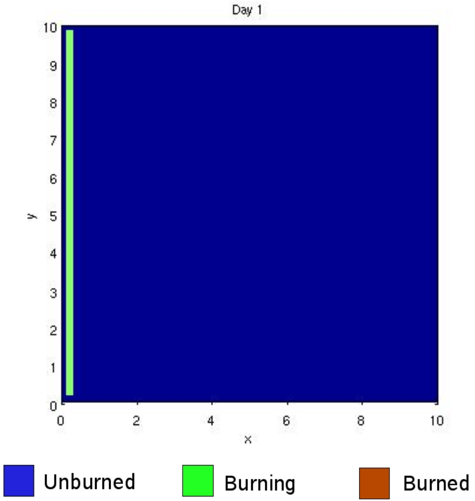

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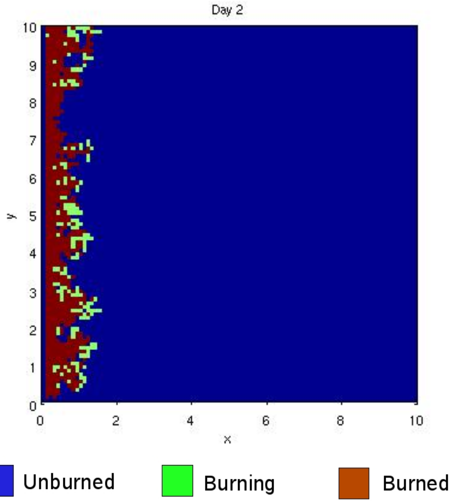

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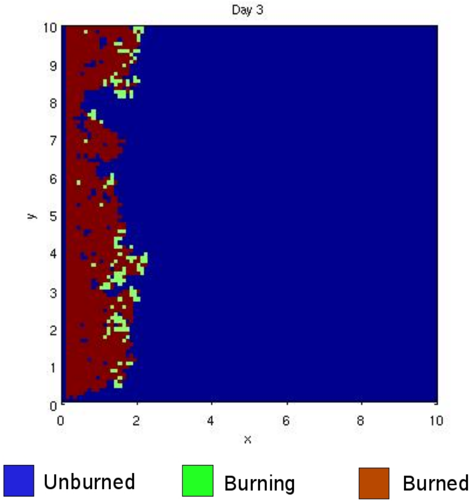

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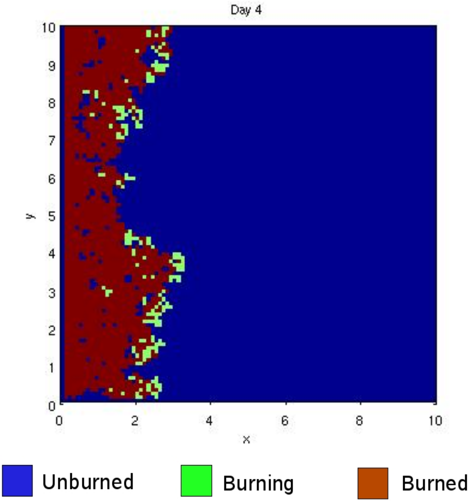

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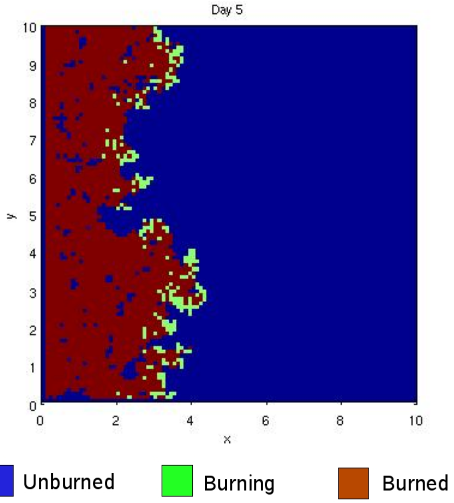

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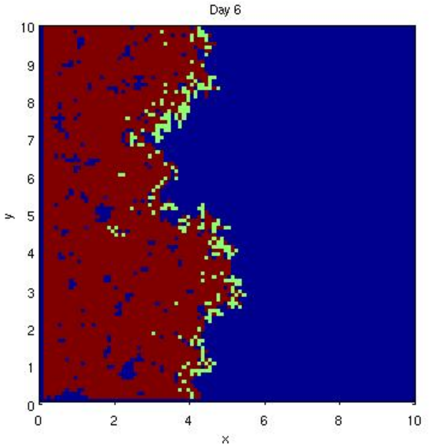

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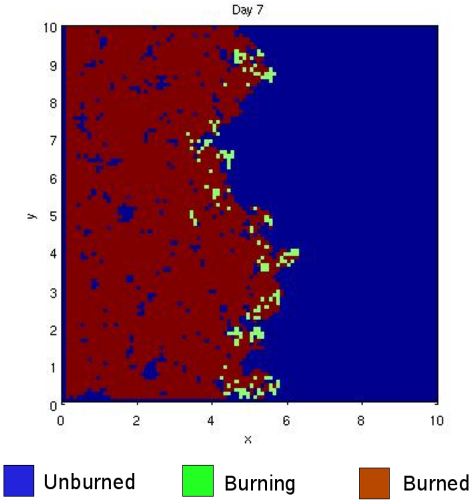

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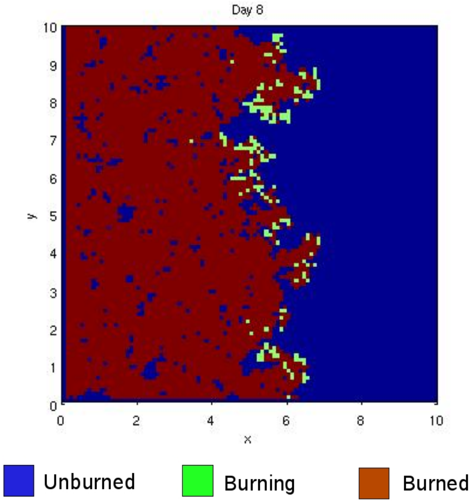

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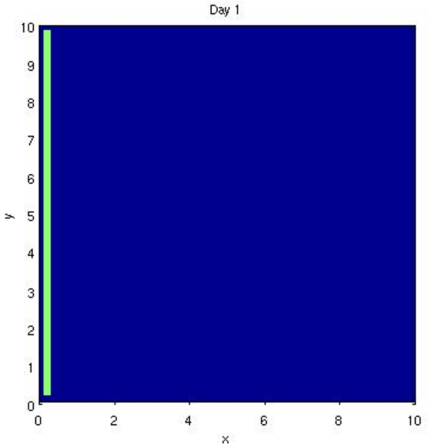

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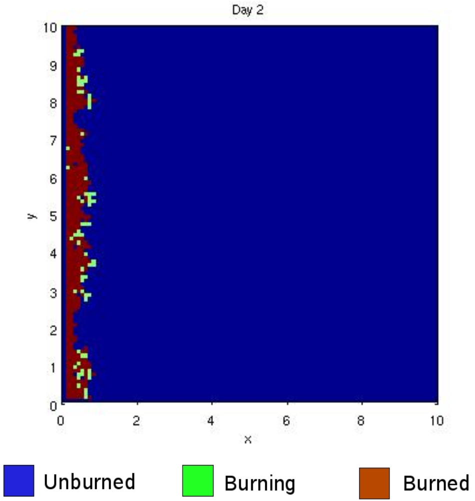

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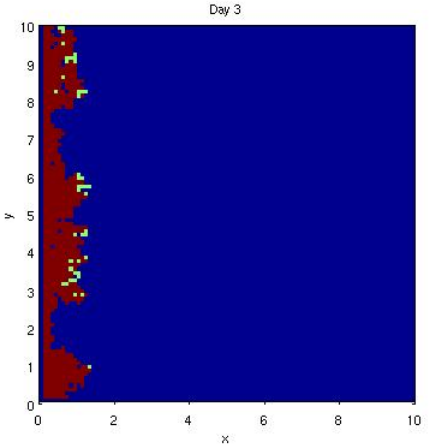

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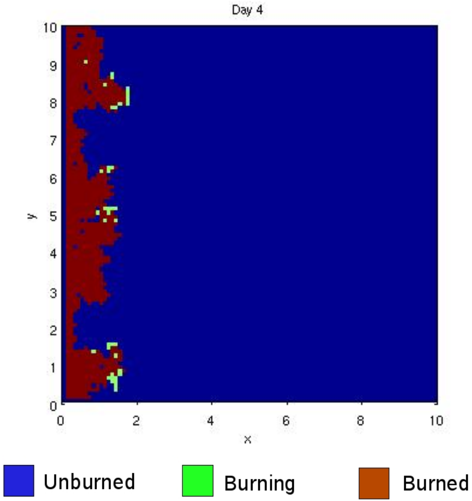

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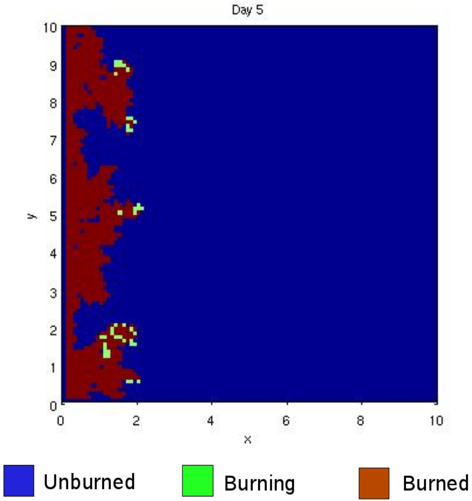

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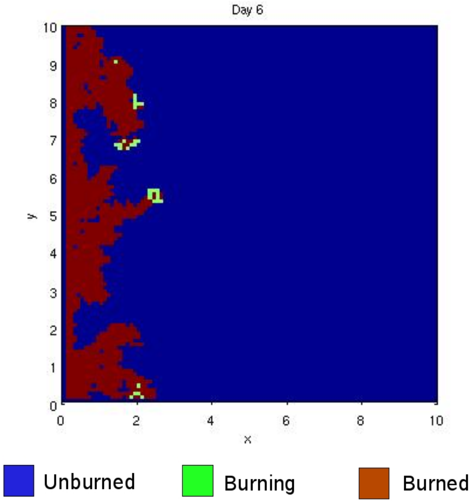

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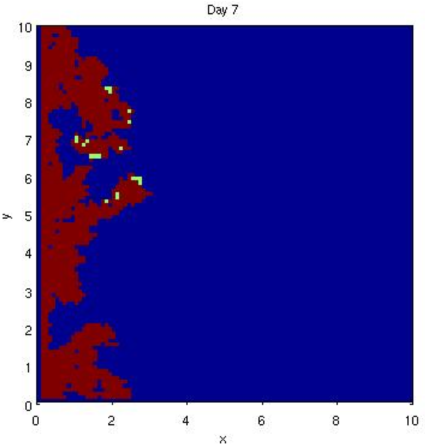

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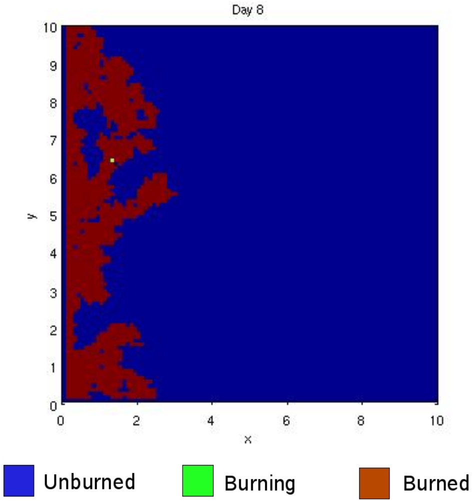
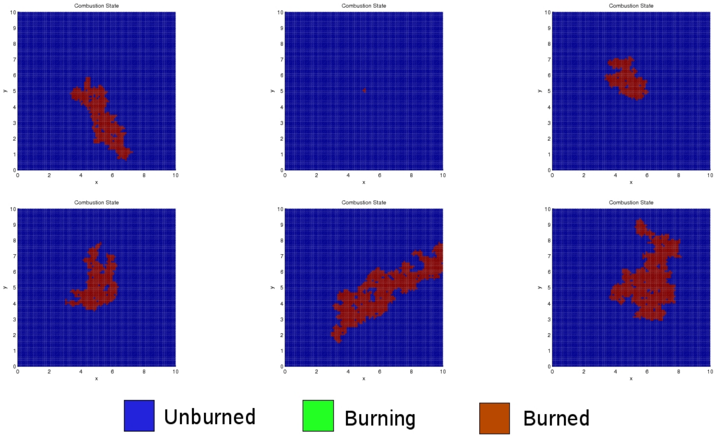


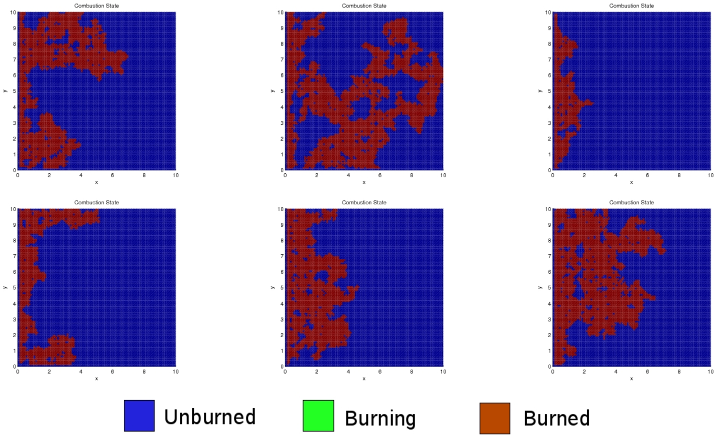
Model Behavior (End Stage Spatial Patterns)

End stage spatial patterns for moist duff with center ignition.



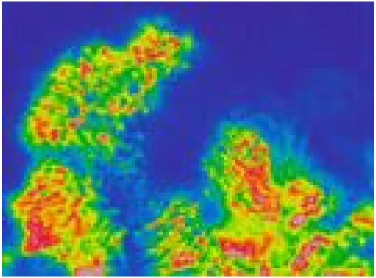
Model Behavior (End Stage Spatial Patterns)

End stage spatial patterns for moist duff with edge ignition.



Model Behavior (Comparison to Field Observation)

Spatial patterns predicted by the model qualitatively agree with field observation.

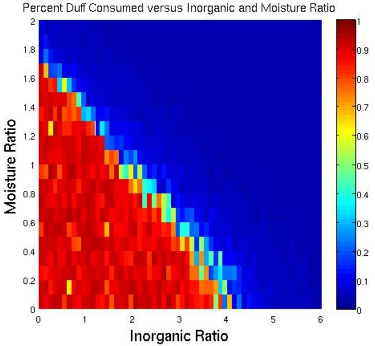


Model Behavior (Comparison to Field Observation)

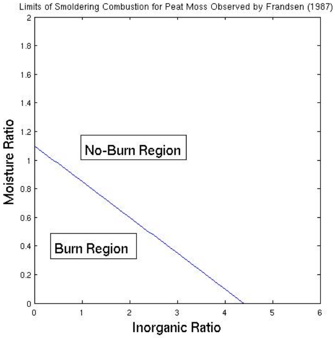
Spatial patterns predicted by the model qualitatively agree with field observation.

Model Behavior (Limits of Smoldering Combustion)

The limits of smoldering combustion predicted by the model qualitatively agree with empirical data.



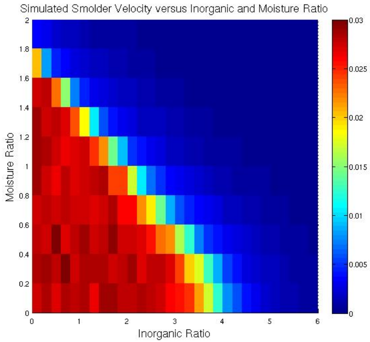
Predicted limits for spruce pine duff.



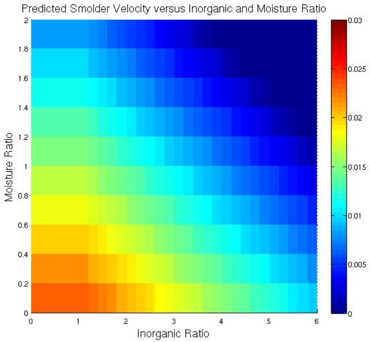
Observed limits for peat (Frandsen, 1987).

Model Behavior (Smolder Velocity)

Smolder velocities predicted by the model qualitatively agree with empirical data.



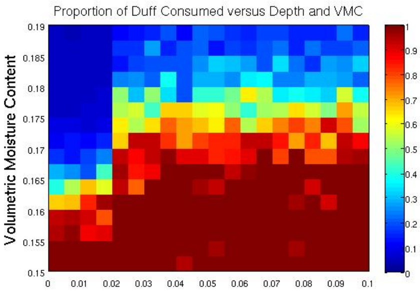
Simulated smolder velocity.



Statistical Model by Frandsen (1991).

Model Behavior (Duff Depth and the Limits of Smoldering Combustion)

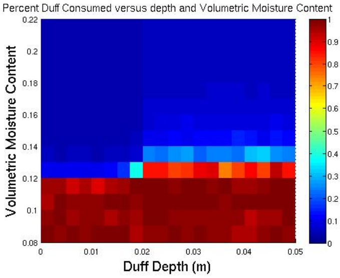
Duff depth influences the limits of smoldering combustion (Miyanishi 2001).



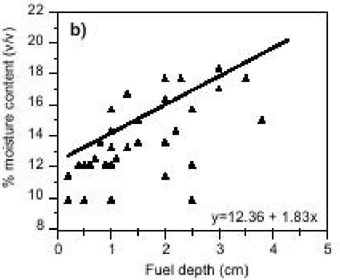
Predicted response of duff consumption to duff depth.

Model Behavior (Duff Depth and the Limits of Smoldering Combustion)

Limits of smoldering combustion predicted by the model qualitatively agree with empirical data.



Predicted limits for spruce pine duff.



Observed limits for peat (Miyanishi, 2002).

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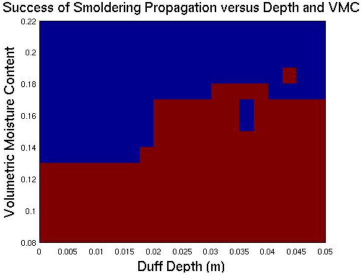
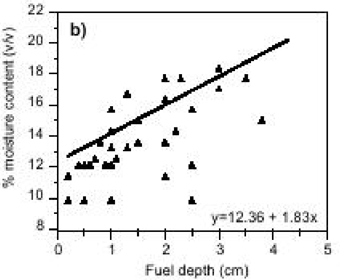


Predicted limits for spruce pine duff.



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Conclusions

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Invitation to new graduate students: there many opportunities to improve upon this model.

Conclusions: Future Work

The model is easily modified to account for the following phenomena:

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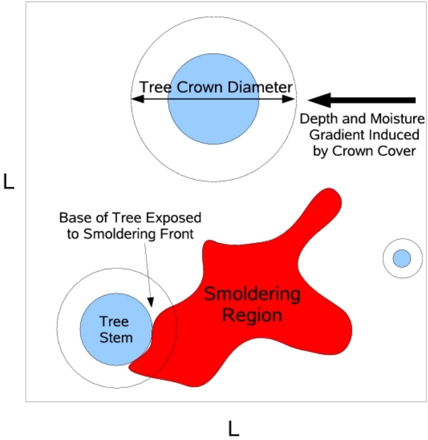
- tree mortality induced by smoldering duff.
- duff depth reduction.

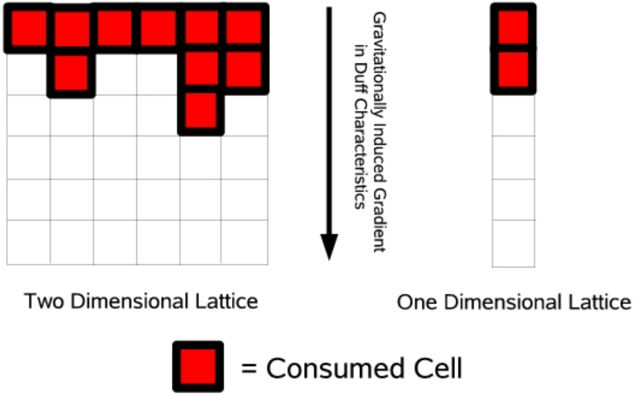
Conclusions: Future Work

Modification: Tree Mortality.



Conclusions: Future Work

Modification: Duff Depth Reduction.

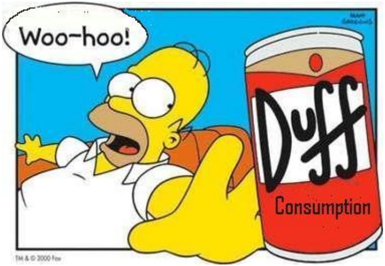


Conclusions

Repeated simulation of the model with the above modifications could yield useful information concerning various aspects of duff consumption useful to foresters and ecologists in their efforts to restore forest health.

Thanks!

Special thanks to my committee for their guidance and wisdom: Dr. Elizabeth Burroughs, Dr. J. Morgan Varner, Dr. Christopher Dugaw.



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Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Can. J. For. Res.*, **17**:1540-1544.

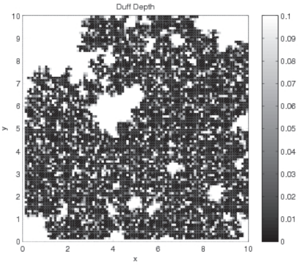
Frandsen, W.H. 1991. Burning rate of smoldering peat. *Northwest Science*, **65**:166-172.

Miyanishi, K. 2001. Duff consumption. In *Forest Fires - Behavior and Ecological Effects*, pp. 437-474. Academic Press, San Diego, CA.

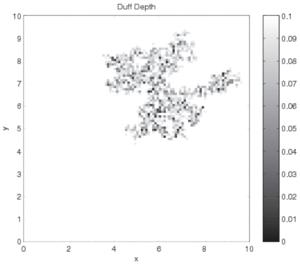
Miyanishi, K. and E. Johnson. 2002. Process and patterns of duff consumption in the mixed wood boreal forest. *Can. J. For. Res.*, **32**:1285-1295.

Varying Depth

Output from the modified model after 8 simulated days where duff depth is allowed to probabilistically decrease according to duff conditions.



20% GMC.



110% GMC.