Modeling the effects of fire severity on boreal ecosystems in Alaska

The organic layer is of fundamental importance in boreal ecosystems for its influence in soil thermal and hydrologic regimes that determine (1) active layer dynamic and permafrost stability, (2) environmental conditions for regeneration.

(Kasischke and Johnstone 2005)

(Johnstone et al. 2010)
In the present study, we used a process-based modeling approach to examine the response of the organic layer depth to fire and how this response influences permafrost stability, carbon cycling and vegetation composition.
To forecast future changes in ecosystem structure and functions in response to warming and fire regime, ecosystem models need to properly reproduce:

(1) the thermal and hydrological properties of the surface OL and mineral soil horizons,

(Zhuang et al. 2002)

(Yi et al. 2010)
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(2) the re-accumulation of organic horizons after fire,

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(1) the thermal and hydrological properties of the surface OL and mineral soil horizons,
(2) the re-accumulation of OL horizons after fire,
(3) the spatial and temporal variability in the removal of organic horizons after fire.

→ Lookup table approach

<table>
<thead>
<tr>
<th>Soil Drainage</th>
<th>Fire Season</th>
<th>Relative Area Burned</th>
<th>Fire Severity Category</th>
<th>Relative Amount of Aboveground Vegetation Biomass Consumed$^a$</th>
<th>Relative Amount of Organic Soil Consumed by Depth$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>early</td>
<td>small</td>
<td>low</td>
<td>0.16</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>large to ultralarge</td>
<td>moderate</td>
<td>0.24</td>
<td>0.69</td>
</tr>
<tr>
<td>Wet</td>
<td>late</td>
<td>all sizes</td>
<td>high</td>
<td>0.32</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>all seasons</td>
<td>all sizes</td>
<td>NA</td>
<td>0.16</td>
<td>0.48</td>
</tr>
</tbody>
</table>

$^a$Based on French et al. [2002].
$^b$Based on E. Kasischke (unpublished data, 2010).

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Towards a much finer representation of continuous variation in fire severity effects across the landscape.

(Barrett et al. 2010)
The set of observation:

- 178 sites dominated by **black spruce** in Alaska
- Data collected from 31 fire events between 1983 and 2005.

**Relative Organic Layer loss**

\[ \text{ROL} = \frac{\text{OL loss}}{\text{pre-fire OL thickness}} \]
- In lowlands, the level of soil moisture controls fire severity effects on the organic layer.
- In uplands and slopes, the effects of fire severity on the organic layer are primarily controlled by fire characteristics, drought and soil moisture.

- Drainage is the most important factor affecting the relative reduction of the organic layer after a fire ($R^2 = 24.8\%$).
Integration in TEM

Environmental Module (Daily)

Dynamic Soil Layer Module (Annual)

Ecological Module (Monthly)

Fire Disturbance Module (Monthly)

ALFRESCO (Annual)
Before incorporating new fire severity algorithm into TEM there was no effect of drainage on post-fire organic layer reduction ($F=0.13$, $p=0.878$).
Integration in TEM

- Organic layer recovery
- Landscape pattern of fire severity
Incorporation of new fire severity algorithm resulted in the simulated relative reduction in the organic layer being significantly correlated with observations ($p<0.01$).

The model now reproduces the effects of landscape-level drainage on the reduction of the soil organic layer after fire.
Assessment of the relative impacts of future warming and fire intensification on carbon balance and permafrost vulnerability.

- Warming scenario: historical CRU records + CCMA projection (A1B emission scenario)
- No Warming scenario: detrended air temperature using cubic spline fitting.
- Fire intensification scenario: historical records from AK fire service + ALFRESCO projections
- Constant fire scenario: constant fire return interval computed from historical records

<table>
<thead>
<tr>
<th></th>
<th>Fire Intens. (FI)</th>
<th>No Fire Intens. (noFI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warming (W)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>No Warming (NoW)</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Forecast ecosystem vulnerability
The increase in simulated active layer depth is dominated by the effects of fire intensification in decreasing organic layer thickness. The simulated reduction of the organic layer thickness is dominated by the effects of fire intensification, and results in a 6 cm decrease in organic layer thickness across the landscape by 2100.

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Soil carbon stocks is decreasing from loss by combustion and decomposition by 9.8 gC.m-2 by 2100.

(Genet et al. 2013)
The impact of the co-existing warming and fire intensification in black spruce boreal forest induce:

1. A decrease of the organic layer depth.
2. A degradation of the permafrost.

These two responses induce significant carbon loss in black spruce forest.

Yet, a thinner OL and fire intensification in response to future warming should result in a suitable environment for deciduous tree recruitment.

A key question is the degree to which increased productivity of deciduous forest offsets the carbon loss related to permafrost degradation.

(Johnstone et al. 2010)
Identifying Indicators of State Change and Forecasting Future Vulnerability in Alaskan Boreal Forest
Post-fire vegetation succession

Initial recruitment

VEGETATION SUCCESSION

(A)

Short fire interval

Light burn or long fire interval

(B)

Severe fire

Conifers establish

(C)

Short fire interval

Conifers establish

(EVERGREEN TRAJECTORY)

MIXED TRAJECTORY

DECIDUOUS TRAJECTORY

(Johnstone et al. 2010)
The TEM model was coupled with a dynamic vegetation model where vegetation communities are composed of various plant functional types that are competing for light and water and nitrogen uptake.
Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest

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Fig. 1  Map of the study sites in interior Alaska (modified from Johnstone et al., 2009). Solid gray polygons indicate areas that were burned in 2004. Study sites (n = 90) are shown as filled black squares in fires that intersected the Dalton, Steese, and Taylor highways. Because of the small scale of the map, symbols overlap for some sites.
Relative influence and partial dependency plots for variables in a boosted regression tree predicting relative spruce dominance.
Recruitment: proposed model

Drainage

**Subhygric**
- Failure → Thermokarst model

**Mesic**
- Pre-fire vegetation (PFV)
- \( PFV = \text{decid.} \)
- Deciduous trajectory
- High/moderate
- low
- Fire severity

**Xeric**
- Pre-fire vegetation (PFV)
- \( PFV = \text{everg.} \)
- Fire severity
- \( PFV = \text{decid.} \)
- Deciduous
- \( PFV = \text{everg.} \)

Fire severity

Pre-fire stand age

Thermokarst model

- Failure → Thermokarst model

Deciduous trajectory

Evergreen trajectory

- \(< 50 \text{ yr} \)
- Failure

- \(> 50 \text{ yr} \)
- Mixed trajectory

Deciduous trajectory

Mixed trajectory

- \(< 50 \text{ yr} \)
- Failure

- \(> 50 \text{ yr} \)
- Mixed trajectory
Vegetation trajectory: “pure” trajectories

The time of the transition from shrub to forest vegetation will be function of the forest vegetation (earlier for deciduous than for evergreen forest forest) and the browsing intensity.
Vegetation trajectory: “mixed” trajectories

The time of the transition from deciduous to evergreen forest vegetation will result from deciduous mortality, moss layer thickness and fire return interval. Both moss productivity and mortality will be a function of climate and local drainage conditions.
Effects of fuel treatments on organic layer depth, thaw depth and seedling recruitment at sites located in recent prescribed fire.