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## New development and application needs for Earth system modeling of fire–climate–ecosystem interactions

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Wildfire, climate and ecosystem are interactive components of the Earth system (Bowman *et al* 2009, Andela *et al* 2017). Climate and fuel moisture, which is heavily impacted by atmospheric conditions, are primary drivers for fire occurrence and behavior, while vegetation provides necessary fuels for combustion (Pyne *et al* 1996). On the other hand, fires can feedback climate and ecosystems by emitting carbon and aerosols (Kloster *et al* 2010, Ward *et al* 2012, Urbanski 2014), which can affect the global carbon cycle and atmospheric radiation. Removal of trees by fires and subsequent multiple-year vegetation regeneration modify albedo and leave area index (Gitas *et al* 2012, French *et al* 2016), which would further change the land–air fluxes of heat, water and momentum.

Research has traditionally focused on the wildfire impacts of climate and vegetation, using the approaches developed mainly based on empirical and statistical weather–fire behavior relationships as well as empirical and process-based vegetation–fire relationships. Recent studies have turned more attention to the feedbacks of fires to climate and ecosystems (Liu *et al* 2013). A most sophisticated tool for understanding the complex interactions is Earth system modeling such as the Community Earth System Model (CESM) (Hurrell *et al* 2013). An Earth system model includes atmospheric models to provide the environmental conditions for wildfires such as droughts, to simulate atmospheric radiation and climate effects of fire carbon and particle emissions, and to calculate the disturbances in land–air fluxes due to fire induced changes in vegetation coverage, albedo and roughness. An Earth system model also includes vegetation models such as dynamic global vegetation models (DGVMs) (Bachelet *et al* 2001) to simulate the carbon, water and nitrogen cycles in the terrestrial ecosystems driven by atmospheric chemistry, climate, land-use and land-cover types and disturbances such as fires.

An urgent issue in fire–climate–ecosystem interactions is the future fire trends under climate change. Many general circulation models (GCMs) have

projected significant climate change by the end of this century due to the greenhouse effect. This would affect weather conditions important to fire ignition and spread, including drought and heat wave frequencies (IPCC 2013), wind strengths (McVicar *et al* 2012), and potential for lightning changes (Clark *et al* 2017). Climate change would also affect fuel loading and moisture (Flannigan *et al* 2015), which would affect all aspects of fire behavior (burned area, occurrence, duration, intensity, severity, seasonality, etc) (Spracklen *et al* 2009). A special power of the Earth system models is their capacity in projecting future climate change with the ecological and environmental consequences and feedbacks (Kloster *et al* 2012, Li *et al* 2014, Ward *et al* 2016).

In a recent study, Wotton *et al* (2017) extended the fire impacts of climate change from fire behavior to fire suppression in the Canadian boreal forest. The authors projected future fire intensity based on climate change projections from three GCMs and the Canadian Forest Fire Behavior Prediction System and found that the number of crown fires would likely increase. They examined future operational fire intensity thresholds used to guide fire suppression decisions and showed that the fraction of fires that are beyond the capacity of suppression would increase substantially, even doubling by the end of this century in some climate change scenarios.

These findings suggest the needs for new development and applications with Earth system modeling of fire–climate–ecosystem interactions. First, the human factor for fire termination should be treated more dynamically. Fire termination is an essential process besides fire ignition and spread in any fire module of a DGVM. It is determined by both natural factors such as weather, fuel availability and geographic barriers and human causes such as suppression. The fraction of unsuppressed fires in most vegetation models is assumed to be inversely proportional to population density with constants determined empirically or based on historical data (Pechony and Shindell 2010). The

result of increasing fires unsuppressed under changing climate from Wotton *et al* (2017) suggests that climate factor needs to be included in the calculation of the fraction.

Second, the post-fire vegetation restoration could be different between the present and future. Besides DGVM simulation of post-fire dynamic tree regrowth, an Earth system model also can predict the long-term climatic impacts through specifying fire-induced land-surface property disturbances based on historical data. More crown fires and larger fraction of unsuppressed fires revealed in Wotton *et al* (2017) mean longer periods of tree regeneration in the future under climate change than the current estimation. Thus, the fire feedbacks to climate and impacts on the carbon cycle related to fire emissions and uptake by new generated trees would be more significant in the future. Thus, there might be a problem with the use of the historical approach in Earth system modeling to investigate the feedbacks of fires to climate and ecosystems in the future.

Finally, the black carbon (BC)–albedo–snow feedback induced by wildfire could be weaker than previously estimated. Boreal fires contribute more BC to the Arctic than anthropogenic sources during the summer (Stohl *et al* 2006) and the deposition of BC reduces albedo and increases solar radiation absorbed by the surface, which in turn accelerates snow and ice melting (Hansen and Nazarenko 2004). However, wildfires play an opposite role by removing trees, leading to more snow coverage and therefore larger albedo (French *et al* 2016). This would partially offset the snow and ice melting role of the BC–albedo–snow feedback. The finding of more crown fires under climate change from Wotton *et al* (2017) suggests an even greater importance of the tree-removal and snow increase effect in the future. Simulations with Earth system models are needed to have a quantitative comparison between the two opposite roles.

Regional differences are concerned when making global implications of the findings from Wotton *et al* (2017). In tropical forests, there are no snow related feedbacks; with more water and energy supply, tree regeneration might be less impacted even with more crown fires in the future. In a savanna, the above issues could be less significant because almost all fuels are removed by fires. Even in the boreal regions outside Canada, fire suppression management and thresholds could be different, which would lead to varied impacts of climate change on crown fires and unsuppressed fire fraction. This concern could be addressed through Earth system modeling and comparison of the impacts of climate change on fire severity and suppression in various geographic regions.

Another concern is the magnitude of projected climate change and fire impacts. Among the three GCMs used for this study, the Hadley GCM has typically wetter conditions overall across much of the forested area of Canada. Therefore, the fire danger levels are lower

and the summary results of fire behavior indices which emphasize the extremes are less remarkable. Thus, the future increase in crown fires and fraction of unsuppressed fires is generally much smaller for Hadley GCM than the other two GCMs. Analyses of climate change scenarios from other GCMs would provide more robust evidence and quantitative estimates of the magnitude for the fire impacts of climate change.

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