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The Impact of Terrain and Fire Duration on Boreal Fires in the LPJmL-SPITFIRE Fire-Enabled Dynamic Global Vegetation Model

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Abstract

Fire-enabled Dynamic Global Vegetation Models (DGVMs) are used to model fire-vegetation interactions and their impacts on global vegetation dynamics. Previously, these DGVMs have performed poorly in the boreal zone. The challenge of modelling fires in the boreal zone has been addressed by several DGVMs by increasing fire durations, from previous limits of less than a day, to multiple days. We investigate improvements to modelling boreal fires in the LPJmL-SPITFIRE DGVM by implementing a multiple-day fire spread algorithm. In addition, we include an empirically derived terrain fragmentation function to account for the impact of terrain ruggedness on limiting fire spread for larger, longer-duration fires. Our work is conducted in two parts: first, we use satellite data to investigate the impact of terrain ruggedness on burnt area at the 0.5° by 0.5° resolution typical of DGVMs, for latitudes greater than 50°. We demonstrate that terrain fragmentation acts as a significant limit on fire size, and derive an empirical function based on our data analysis that describes this effect. The second part of our work consists of the implementation of a multiple-day fire spread algorithm in combination with the terrain ruggedness limitation function in the LPJmL-SPITFIRE model. We find that this results in a significant improvement of fire spread calculations in the boreal zone. The results of this work represent a useful addition to LPJmL-SPITFIRE, in addition to DGVMs in general that do not incorporate the effects of terrain-based landscape fragmentation.

1. Introduction

Dynamic Global Vegetation Models (DGVMs) model processes including vegetation establishment, growth, and mortality as they respond to solar radiation and global water and carbon cycles. An important component of many such models is the incorporation of a coupled fire model to calculate fire-related plant mortality as well as fire impacts on the global carbon cycle. The Lund-Potsdam-Jena managed Land (LPJmL) Dynamic Global Vegetation Model calculates vegetation dynamics on a grid with cells of size 0.5° × 0.5° and is coupled to the Spread and InTensity of FIRE (SPITFIRE) global fire model (Schaphoff et al., 2018; Thonicke et al., 2010). SPITFIRE models ignition events and fire danger, and takes a process-based approach to modelling the spread of the resulting fires, based on the Rothermel equation (Thonicke et al., 2010; Rothermel, 1972; Albini 1976). The work described herein focuses on the fire spread component of SPITFIRE, coupled with the latest version of LPJmL, LPJmL5.3.

A common issue in DGVMs has been inaccuracy in predicting fire in boreal regions (Ward et al., 2018). Fires in boreal forests often have longer durations (Andela et al., 2019). Therefore, several models have sought to improve fire modelling in boreal regions by introducing longer fire durations (Ward et al., 2018). LPJmL-SPITFIRE currently limits fire duration to a maximum of 241 minutes, relying on a modelling approach that replaces large fires with a larger number of small fires (Thonicke et al., 2010). While this approach is successful at lower latitudes, the model currently under-predicts burnt area in the boreal zone to a significant extent.

To improve upon this, we examine the impact of introducing longer fire durations in LPJmL-SPITFIRE. As a consequence of introducing these longer in duration, and therefore larger, fires, the impacts of various fuel bed fragmentation barriers on fire size become more significant. We therefore examine the impact of terrain ruggedness on limiting fire spread, and implement a function to represent this in the model.

While some fire-enabled DGVMs account for the effect of landscape fragmentation on limiting burnt area, the functions used for this are based on heuristic arguments, and are not derived from theoretical calculations or observed data, and many models omit this effect entirely (e.g. Pfeiffer et al., 2013, Rabin et al., 2017). We seek to improve upon this by deriving an empirical function, based on a satellite data analysis, that can be implemented in DGVMs. A combination of this function and multiple-day fire spread results in significant improvements to the fire spread component of LPJmL-SPITFIRE in the boreal zone.

2. Terrain Limits on Fire Spread

We examine the impact of terrain ruggedness on fire spread using the 250 m GMTED2010 Digital Elevation Model (DEM), courtesy of the U.S. Geological Survey. We compute the Vector Ruggedness Measure (VRM) at the original resolution of the DEM and take the median of this value over 0.5° × 0.5° grid cells, matching the resolution of LPJmL-SPITFIRE, using Google Earth Engine (Gorelick et al., 2017). We then compare these values for each grid cell to the size of individual fires in the grid cells from 2003 to 2016 using data from the Global Fire Atlas (Andela et al., 2019). We divide fires by the main landcover type burned and report results for landcover types with over 10 000 observed fires that have ignition points at latitudes greater than 50°.

We bin fires by VRM, with bin widths calculated using the Freedman-Diaconis rule found to produce the most consistent results. We find that the most significant impact of VRM on fire size is its role as a limit on the size of the largest fires, with significantly less impact on the median fire size calculated in each bin. The left panel in Figure 1 shows functions of the form: maximum fire size $= \frac{a}{\mathrm{VRM}+b}$, where a and b are constants, fit to the maximum fire size in each bin using least squares regression, with R^2 values shown in the legend.

These functions collapse into two bands, with Evergreen Needleleaf Forests, Mixed Forests, and Grasslands generally having higher maximum fire sizes and Open Shrublands, Deciduous Needleleaf Forests, and Woody Savannas having smaller maximum fire sizes. A potential explanation may be that additional causes of fuel bed fragmentation beyond those due to terrain ruggedness may result in reduced fuel bed connectivity for the lower band of functions, amplifying the effect of terrain fragmentation. However, further study is required to examine the differences between the two bands.

We use the function derived for Mixed Forests for the initial implementation of a maximum fire size function in LPJmL SPITFIRE. This is due to several factors, including that 70% of fires in the landcover types we examine at latitudes over 50° fall into the upper band of maximum fire size functions, of which the mixed forest function imposes the largest limit, and that the landcover types in the lower band are not well represented in the LPJmL DGVM. The function is:

$$\text{maximum fire size} = \frac{60}{\mathrm{VRM} + 1.6 * 10^{-4}},$$

and is plotted in the right panel of Figure 1. Maximum fire sizes in each bin, to which the function is fit, are shown in black, and raw individual fire sizes are shown in grey. This limit is significantly closer to the bulk of the fire size distribution for VRM values above 0.003, potentially due to fires before this value being extinguished before they can reach their significantly higher and, at low VRM values, potentially non-existent, maximum terrain limits. While our current implementation treats this as a fixed maximum fire size, further work should be undertaken to examine the conditions under which this limit can be surpassed due to extreme fire behaviour, in particular to avoid artificially strong fire size limitation under extreme fire conditions.

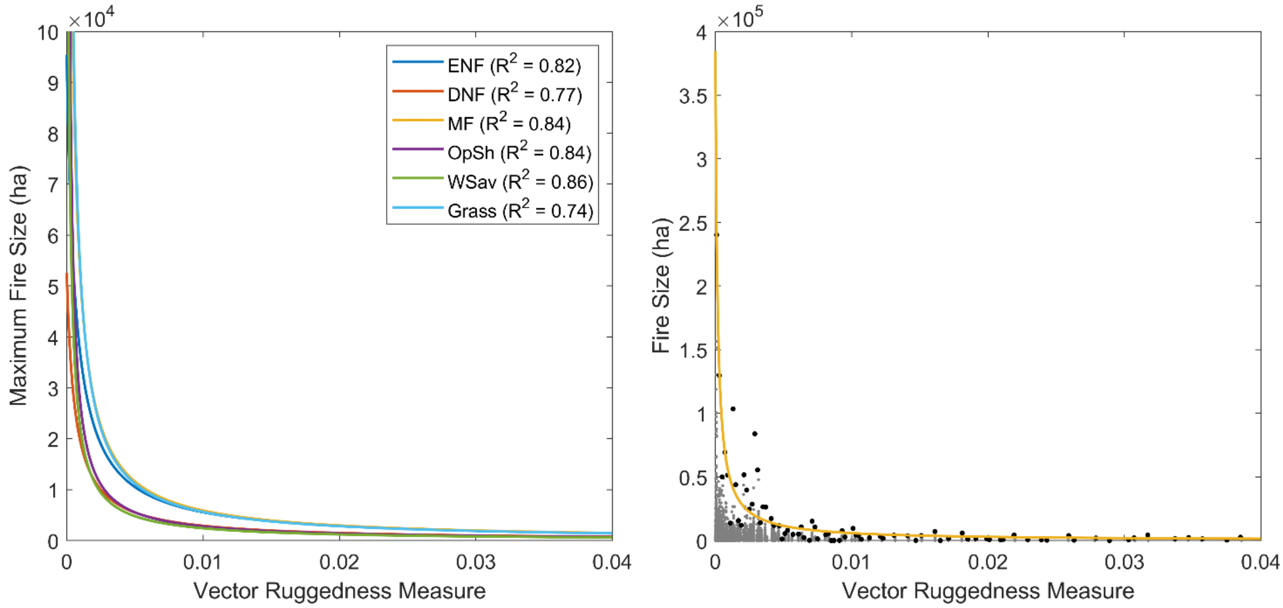

Figure 1 – Derived functions for the maximum fire size as a function of median vector ruggedness measure over a 0.5° × 0.5° grid cell for various landcover types (left panel). Abbreviations are as follows: ENF – Evergreen Needleleaf Forests, DNF – Deciduous Needleleaf Forests, MF – Mixed Forests (combinations of broadleaf and needleleaf trees), OpSh – Open Shrublands, WSav – Woody Savannas, Grass – Grasslands. The function for Mixed Forests is shown in the right panel with the bin maxima to which this function is fit as black points and individual fires from the Global Fire Atlas shown in grey.

3. Implementation into LPJmL-SPITFIRE

To improve the modelling of boreal fires in LPJmL-SPITFIRE we implement a function that calculates fire spread over multiple days. This function calculates burnt area based on fire spread in an elliptical shape, as in the original SPITIFRE formulation by Thonicke et al. (2010), with ellipses continuing their growth on subsequent days in the absence of extinction events, or the reaching of terrain limits. All active fires in a grid cell are extinguished if there is no calculated increase in fire size for any fires on a given day, or if the Fire Danger Index (FDI), which we calculate based on the Vapour Pressure Deficit (VPD) as in Drueke et al. (2019), falls below a threshold value of 0.005. While this produces reasonable results, further investigation is required to implement a more sophisticated approach to fire extinction caused by, e.g., precipitation in future versions of this model. At present we rely on the impact such events have on reducing the Fire Danger Index.

To avoid excessive computational costs, we limit the number of days that fires burn to 14. This is longer than 95% of fires in the Global Fire Atlas and should therefore not be excessively limiting. In addition, we modify the fire duration function from Thonicke et al. (2010) to allow for longer burning on individual days. The current function results in very short median fires, lasting about 1 hour even when allowing for a maximum fire duration of 12 hours. We set a fixed fire duration of 12 hours per day, relying on a reduced rate of spread to limit fire sizes under wetter conditions. We choose 12 hours per day as fire spread often reduces significantly at night (e.g. Balch et al., 2022). This may be further refined in future, e.g. by limiting fire spread to times when the VPD thresholds derived by Balch et al. (2022) are exceeded.

We examine the impact of this change in fire duration by starting a fire in the model on the day, and in the same grid cell of each fire in the Global Fire Atlas. We then compare the burnt area in the model to the Global Fire Atlas, effectively comparing the fires in the model to their observed counterparts. This approach allows for an examination of the model's fire spread calculations without the additional ambiguity introduced by the parametrization of ignition events and their conversion into spreading fires based on an FDI. Because the FDI, which requires some tuning, is only implemented in the extinction threshold, this significantly reduces the impact of tuning on the model results examined here.

Figure 2 shows a timeseries of burnt area for model simulations with multiple-day fires compared to the Global Fire Atlas, and to a previous version of SPITFIRE (described in Schaphoff et al., 2018). The implementation of multiple-day fires results in a significant improvement in the model at latitudes greater than 50°, and the implementation of terrain fragmentation fire size limits improves the model further. The previous version of SPITFIRE simulates a negligible amount of burnt area for these fires due to the low fire duration.

Figure 2 – Annual burnt area as a function of time for latitudes over 50° in LPJmL-SPITFIRE and for the same fires in the Global Fire Atlas. The two implementations of LPJmL-SPITFIRE with multiple-day fires (Fragmentation and No Fragmentation) show a significant improvement in reproducing these fires over a previous version of SPITFIRE.

Therefore, the parametrization introduced here represents a significant improvement at the examined latitudes. However, modelled values appear to diverge slightly from the Global Fire Atlas burnt areas in later years. One potential cause for this may be that the Global Fire Atlas divides large burn patches into too many individual fires, e.g. as described by Artés et al. (2019), which grow into individual large fires in LPJmL-SPITFIRE. An additional cause for the difference may be that LPJmL simulates significant encroachment of vegetation into higher latitudes over the examined time period.

This increase in vegetation in the model may also explain excessively high values of burnt area at higher latitudes shown in Figure 3. Of additional interest, a difference map between model runs with terrain fragmentation limits imposed and those without, shown in the bottom right panel, shows the locations where the terrain fragmentation function has the greatest impact. Modelled fires in eastern Russia and Alaska are particularly prone to reaching the terrain fragmentation limits. Therefore, accounting for these limits may be particularly important for studying fires in these areas.

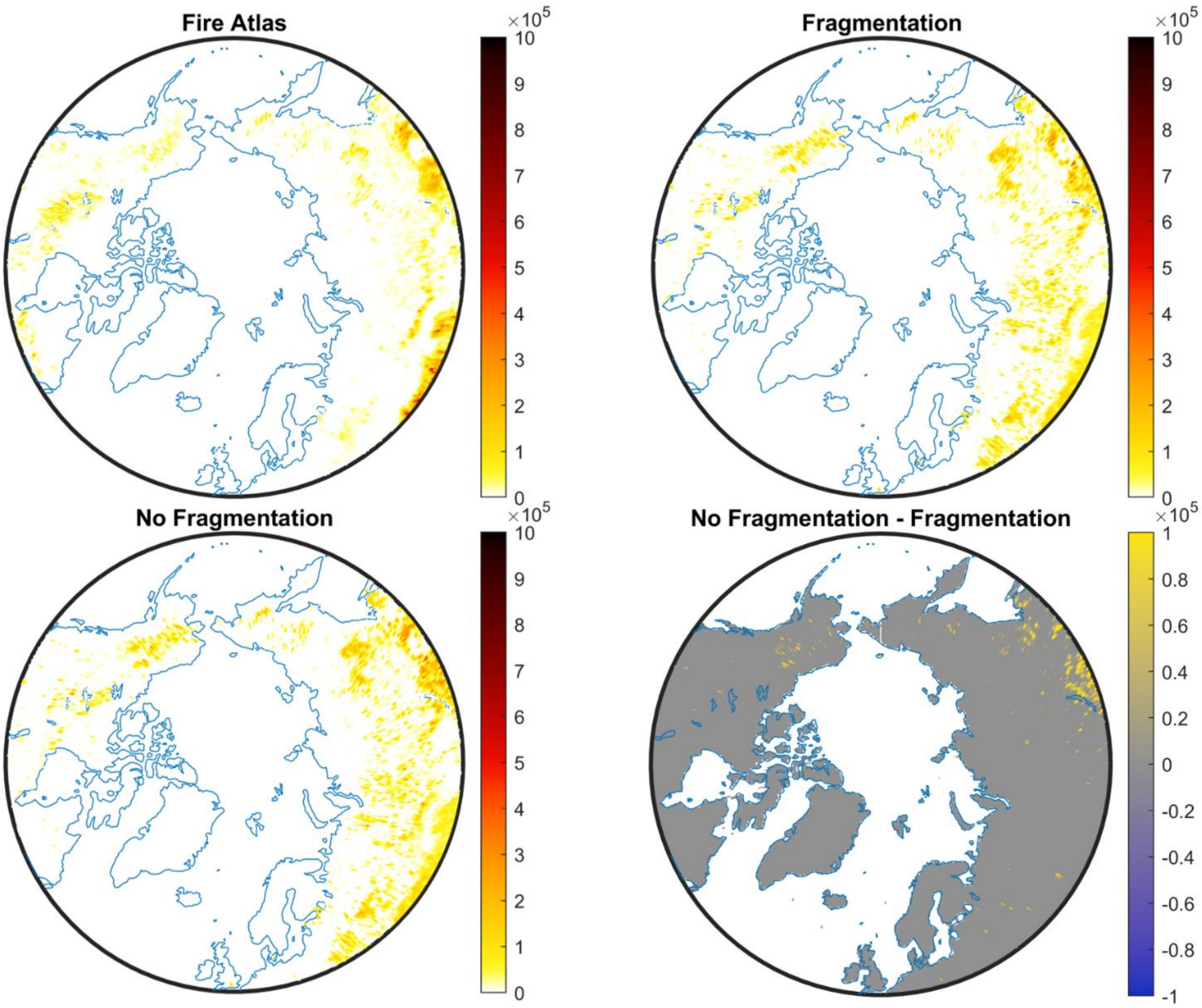

Figure 3 – Burnt area per 0.5° × 0.5° grid cell (in ha) at latitudes over 50°, summed from 2003 to 2016, due to fires in the Global Fire Atlas and the same fires implemented in LPJmL-SPITFIRE with and without fuel bed fragmentation due to terrain ruggedness in the model. The bottom right panel shows the difference between these two sets of results. Colour maps were obtained from www.colorcet.com, based on Kovesi (2015).

4. Conclusions

We implement a multiple-day fire spread algorithm, and a function to account for the effect of terrain fragmentation in LPJmL-SPITFIRE at latitudes greater than 50°. Terrain fragmentation is accounted for by fitting a function of the Vector Ruggedness Measure to the maximum fire sizes observed in the Global Fire Atlas. This function is then implemented as a limit to fire sizes in the model. The multiple-day fire spread algorithm allows fires to burn for 12 h per day up to a maximum of 14 days. In general, our model results compare favourably with the Global Fire Atlas burnt area when simulating the same fires, with differences likely caused in large part by inaccuracies in vegetation modelling at high northern latitudes. Therefore, our results show a significant improvement on LPJmL-SPITFIRE in the boreal zone.

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