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LUÍS MÁRIO RIBEIRO

Contrasting two alternative models for rate of fire spread in a dynamic global vegetation model

Jessica Hetzer[1]*; Matthew Forrest [1]; Thomas Hickler[1,2]

[1] *Senckenberg Biodiversity and Climate Research Centre (SBiK-F). Senckenberganlage 25 D-60325 Frankfurt am Main, Germany, {jessica.hetzer, matthew.forrest}@senckenberg.de*
[2] *Department of Physical Geography at Goethe-University Frankfurt. Altenhoeferallee 1 D-60438 Frankfurt am Main, Germany, {thomas.hickler@senckenberg.de}*

**Corresponding author*

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Abstract

Rate of spread (RoS) is a key determinant of a fire regime and rate of spread models have a long tradition in fire research. Initially they were used to assess fire risk on a local to regional scale. Latest approaches combine them with scalable models to investigate fire risk globally. However, correctly simulating RoS across large spatial extents requires good knowledge of how fuel characteristics vary across the region of interest. For this purpose, both observed fuel characteristics and effective model representation of the characteristics are indispensable. To facilitate investigation of RoS dynamics and fuel characteristics, dynamic global vegetation models (DGVMs) can link vegetation characteristics (e.g., biomass composition, vegetation type) to fuel characteristics and simulate rate of spread over various spatial and temporal scales. Earlier studies compared rate of spread models for various sites of different biomes. Insights in site specific performance thereby supported decision-making regarding the choice of the model. Here, we address this issue for modelled forest types and biomes across Europe incorporating fire-vegetation interaction by a DGVM. We investigate two common rate of spread models: The widely used Rothermel rate of spread model (Rothermel, 1972) as well as a related modified approach proposed by Wilson (1990). Using the global dynamic vegetation model LPJ-GUESS with the fire module SPITFIRE, we show that the two RoS models lead to substantially different rates of spread and area burned in some parts of Europe, while the differences are small in other parts. After further evaluation, such results might guide the choice of RoS model for different regions.

1. Rate of spread models

The study investigates two rate of spread (RoS) models: The Rothermel's Rate of Spread model (Rothermel, 1972) and the related modified approach proposed by Wilson, (1990). In both models, the rate of spread is represented by ratio of the heat received by unburned fuel from the flame (power density of propagation flux) to the heat required to ignite the unburned fuel (Rothermel (1972); Wilson (1990)). More specifically, the rate is calculated by the reaction intensity I_R times the propagation flux ratio ξ, divided by the overdry bulk density ρ_b, the effective heating number ε and the heat of ignition multiplied by a term that includes the wind factor ϕ_W and a slope factor ϕ_S. Both lead to a higher rate of spread in steep terrain where fuel in the upper part is more exposed to flames from further below, as well as forest fires that propagate rate of spread based on flame-exposing down winds.

$$RoS = \frac{I_R \cdot \xi \cdot (1 + \phi_W + \phi_S)}{\rho_b \cdot \varepsilon \cdot Q_{ig}}$$

While the overall equation structure seems quite similar between the Rothermel and Wilson formulations, the rate of spread models differ in the definition and interpretation of the parameters listed above. Main differences can be found in the reaction intensity, propagation flux ratio, and heat of ignition (Weise & Biging, 1997; Wilson, 1990).

The reaction intensity I_R is a measure of energy release per unit area within the combustion zone (Rothermel, 1972; Wilson, 1990). Rothermel interprets this variable as the rate of change of organic matter from a solid to a gas. The approach of Wilson narrows this term focusing on the energy release of the flames driven by pyrolyzed gases only (explicitly excluding energy release from burning char). Minor additional changes of Wilson are the exclusion of the optimal packing ratio in the reaction velocity. Furthermore, fuel moisture is no longer included in the reaction intensity as a source of fire extinction. Instead it affects the rate of spread as a separate term by a probability function.

The propagation flux ratio ξ represents the proportion of the fires power that drives the fire (Rothermel, 1972; Wilson, 1990). Both approaches, Rothermel's and Wilson's, are based on fitted equations, related to field data of surface to volume ratio σ and the packing ratio (measure of how dense fuel is spatially distributed). The equation provided by Rothermel is mainly dependent on σ, as it is considered as a nonlinear driver in multiple equation terms. Wilson aims to simplify that equation based on physical principals of energy transport.

Originally, Rothermel relates the heat of ignition Q_{ig} to the change in specific heat from ambient to ignition temperature and the observed latent heat of vaporization of the moisture (Rothermel, 1972). In turn, Wilson approximates this heat dependent on observations of heat for pyrolysis and heat of vaporization measured in the field (Wilson, 1990).

2. Modelling concept and simulation setup

In this study we use the dynamic global vegetation model LPJ-GUESS, which integrates eco-physiological processes, such as photosynthesis, autotrophic and heterotrophic respiration, and plant growth with individual-based tree population dynamics and biome biogeography (Smith, Prentice, & Sykes, 2001; Smith et al., 2014). The detailed representation of vegetation dynamics enables insights in local forest ecosystem composition as well as large scale spatial trends of vegetation - bridging the gap from stand level to continental scale.

The rate of spread equations are implemented in the fire-enabling module SPITFIRE (SPread and InTensity of FIRE, (Thonicke et al., 2010)). The process-based fire model explicitly considers fuel characteristics by combining environmental fire drivers and linking vegetation traits to fuel class characteristics (fuel classes are live grass and dead 1hr, 10hr, 100hr fuels). SPITFIRE has been proven to be a useful tool to explore fire regimes explaining broad geographic patterns of annual fractional burnt area. For instance, in combination with the LPJ DGVM, the fire regime of boreal forests could be investigated in more detail (Thonicke et al., 2010). The SPITFIRE fire modelling approach has been adopted by several DGVMs, e.g. Yue et al. (2018). Most recently, SPITFIRE has been integrated in LPJ-GUESS (Smith et al. 2014, Forrest et al., (in prep.)), which has been used here. The model was run without land use, i.e. the potential natural vegetation was simulated.

The model setup includes global plant functional types (PFTs) simulated across Europe from 1700 to 2018. While fire processes in LPJ-GUESS SPITFIRE are simulated daily, vegetation dynamics are updated annually. Climate forcing was provided by the daily CRU-JRA data at a 0.5° resolution. This dataset includes monthly maximum and minimum air temperature, precipitation, wet days, wind, and cloud cover from the CRU database (Harris, 2019) merged with a reanalysis product (Harada et al., 2016; Kobayashi et al., 2015), which provides the sub-monthly temporal disaggregation. Slope was not considered.

3. Simulated fire patterns

In this study we compared the rate of spread based on Rothermel (RoS_R) and on Wilson (RoS_W) simulated by LPJ-GUESS. Overall, the RoS_W was higher than RoS_R (Fig. 1), but the differences were generally low between 45 and 55 degrees north. Deviations regarding the underlying calculation increased from Central to Northern Europe. In Southern regions (e.g., Portugal, Western Spain and Greece) comparison also showed spatial clusters in which RoS_R was higher (Fig. 1).

Similarly, to the rate of spread, the fraction of burned area of Wilson was higher than that by Rothermel (Fig. 2). The general pattern of burned area in Europe (with most fires in Mediterranean areas (Chuvieco et al., 2018)) was reproduced by both approaches, but there also exists clear discrepancies between the satellite-derived estimates and the model results. For example, the Rothermel approach has resulted in too sparse burning in Eastern Europe (Fig. 2). In turn, the mountain regions in northern Italy and Sweden are much more pronounced.

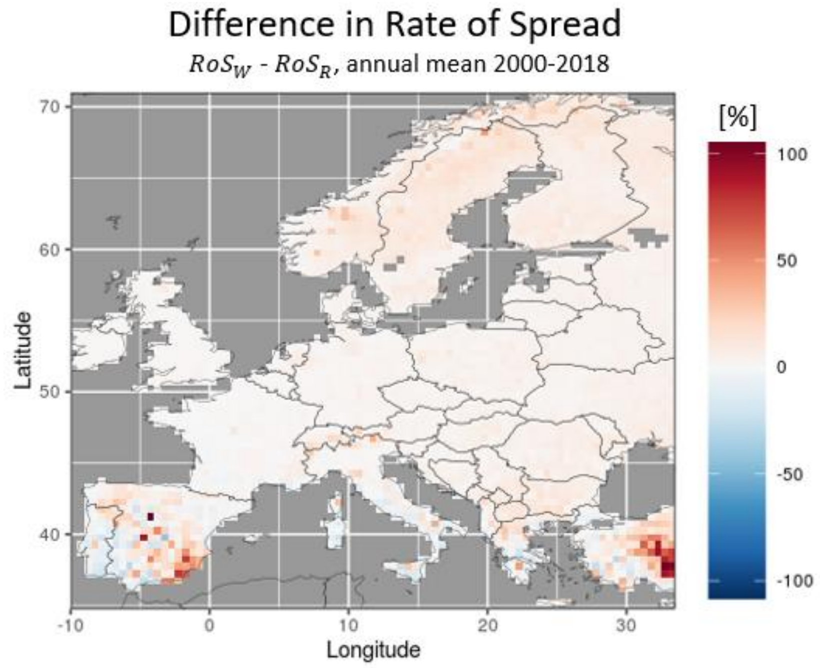

Figure 1- Percentage difference in mean annual rate of spread. Red pixels indicate a higher rate of spread for the Wilson approach than for Rothermel's, blue pixels indicate a lower one.

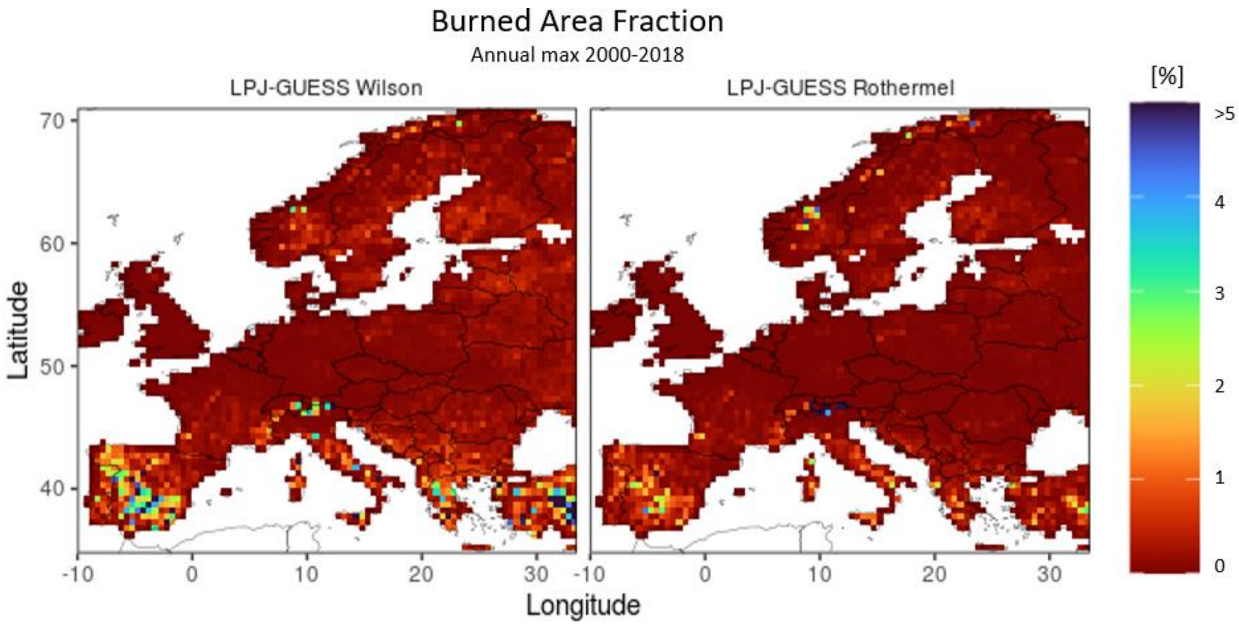

Figure 2- Simulated burned area fraction.

4. Discussion

When embedded in the LPJ-GUESS DGVM, the two RoS models lead to substantial differences in terms of RoS and area burned in some parts of Europe, while the differences were minor at intermediate latitudes. Where the differences are large, the choice of RoS model becomes more crucial. Further evaluation of model results will be necessary to derive suggestions for which model should be used were.

To use the full potential of the coupled vegetation-fire modelling approach, another important next step will be to use the vegetation model with a more regional vegetation representation of Europe (e.g. Hickler et al., 2012) and land use. Only with the actual vegetation in the vegetation model, a detailed evaluation, e.g. of the area burned presented here in Fig. 2, makes sense.

The choice of the RoS model should also depend on regional data to parameterize the RoS model. The equations of Wilson (1990) were parameterised about two decades after Rothermel's first calculations (1972), with more data points included by that time. Therefore, Wilson's function coefficients might have a higher accuracy for the region where the model has been parameterized. However, since the Rothermel model has a long tradition in forest fire research, many observational data are still tailored for the original Rothermel approach.

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