FIREURISK - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT

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Authors:	Maik Billing (PIK), Luke Oberhagemann (guest), Kirsten Thonicke (PIK); Matthew Forrest, Jessica Hetzer, Thomas Hickler (SGN); Simon Bowring, Philippe Ciais (UVSQ), Florent Mouillot (IRD); Eric Koszor, Matthias Forkel (TUD)
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2 Executive Summary

This deliverable describes the metadata of the dataset on simulated fire and vegetation dynamics at three spatial scales and provides examples of spatial and temporal information that can be extracted from these data. The database contains information on simulated future fire regimes using the LPJmLv5.6-SPITFIRE and LPJmLv5.6-SPITFIRE-BASE vegetation-fire models. SPITFIRE is a process-based fire model, developed at PIK, the performance of which was improved and documented in Deliverable D3.3. The Burnt Area Simulator for Europe (BASE) is an empirical burned area model, developed by SGN (with contributions from TUD, LSCE/UVSQ and IRD) that is based on remotely sensed information using generalised linear model (GLM) techniques, provided by several data sources, originated—among others— from FirEUrisk. This deliverable describes the set of future changes in vegetation and fire variables under future climate and land-use change at the European Territory (ET) at 9 km covering the period 2003-2100. The fire-enabled Dynamic Global Vegetation Model (DGVM) was forced with outputs from 5 climate models from the SSP126 and SSP370 climate scenarios (as described in D3.1 as well as the land-use projections corresponding to those climate scenarios (as described in D3.2). The variables provided in this dataset are at monthly (fire) and annual (vegetation) temporal resolution. Simulated changes in the spatiotemporal patterns of fire and vegetation are the result of changes in climate and land use and the resulting fire-vegetation feedbacks.

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5 List of Acronyms

List of Acronyms	
BASE	Burnt Area Simulator for Europe
DGVM	Dynamic Global Vegetation Model
FAPAR	Fraction of absorbed photosynthetic radiation
FPC	Foliage projective cover
FWI	Fire Weather Index
GPP	Gross primary production
HDI	Human development index
IRD	Institut de recherche pour le développement
LPJmL	Lund Potsdam Jena managed Lands
LSCE	Laboratoire des Sciences du Climat et de l'Environnement
NPP	Net primary production
TUD	Technical University of Dresden
UVSQ	Université de Versailles Saint-Quentin-en-Yvelines
VegC	Above- and belowground living vegetation carbon

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6 Climate models and scenarios

The following CMIP6 climate models were applied to LPJmLv5.6. They were selected to match lower, medium and upper bound ranges of the FWI index:

Climate scenario	Climate models used				
RCP2.6	ACCESS-CM2	CanESM5	CNRM-ESM2-1	MPI-ESM1-2-HR	EC-EARTH3
RCP7.0	ACCESS-CM2	CanESM5	CNRM-ESM2-1	MPI-ESM1-2-HR	EC-EARTH3

Table 1: Climate model output used in each scenario to force the LPJmLv5.6 and its embedded fire models. Colours indicate the lowest, medium and upper range of changes in drought code (according to the classification in D3.1).

7 Description of BASE empirical area burned model

The Burnt Area Simulator for Europe (BASE) model was developed by fitting Generalised Linear Models (GLMs) to the ESA FireCCI51 burnt area data over the ET at the 9 km resolution of the climate and land use scenarios. The FireCCI51 dataset was processed in combination with the ESA LandcoverCCI to derive the burnt area fraction per grid cell within an aggregated landcover termed “Woodlands and Shrublands”. This landcover type included all vegetation types in the LandcoverCCI classification except for croplands, grassland and the mosaic classes. The aim was to simulate fire in 'wildlands' (although this term should be used cautiously in this case as most European vegetation is managed to some extent) meaning that the ‘agricultural land’ was excluded. The predictor variables used in BASE are shown in Table 2. The finest temporal resolution of the input variables is monthly, and so the model predicts burnt fraction on a monthly time step. During model development and fitting, the vegetation variables of tree cover, FAPAR (fraction of absorbed photosynthetic radiation), and GPP (gross primary productivity) were represented using remotely-sensed satellite data. However, for the future scenarios presented here, BASE was embedded with LPJmLv5.6 model and these variables were exchanged for the LPJmL vegetation state variables to form a couple fire-vegetation modelling setup (more details in section 3.1). Regarding model structure, the most important variable was the Fire Weather Index (FWI). FWI was combined with GPP_index, the only other monthly term, in an interaction term as this was found to best reproduce the August peak of burning. The Human Development Index (HDI) was also found to be important to capture the temporal trend in burnt area (weakly declining) and spatial patterns (by enhancing burning in the Balkans). Including tree cover as a quadratic term improved the model fit considerably, with the strongest enhancement of burnt at low-to-moderate tree cover. This is attributed to the fact that open systems (i.e. little tree canopy cover) will have a drier microclimate and a greater amount of surface fine fuel (grass, shrubs, lichens and mosses). The other terms had comparatively less influence.

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Variable	Reason	Temporal resolution	Term
Fire Weather Index (FWI)	Fire weather conditions	Monthly	Interaction with GPP_index
GPP_index*	Health and phenological state of vegetation	Monthly	Interaction with FWI
Human Development Index (HDI)	Socio-economic: cultural practices, investment in firefighting, public awareness and legislation	Annual	Linear
Fraction of absorbed photosynthetic active radiation (FAPAR12)	Recent (fine) fuel buildup over last 12 months	Past 12 months	Linear
Human population density (Pop_dens)	People start fires	Annual	Linear
Tree cover (%)	Fuel characteristics and ecosystem openness	Static map	Quadratic
Dominant_type†	Flammability of different tree types	Static map	Fixed effect
Slope	Topography affects RoS, fragmentation, access	Static map	Linear
Topographic Position Index (TPI)	Topography affects RoS, fragmentation, access	Static map	Linear

Table 2: Predictor variables used in the BASE burnt area model, the reason for their inclusion, their temporal resolution, and the form of their term in the model. Variables in bold were quantified with satellite data in the model development and fitting stage, but were replaced with LPJmL model state variables in model runs presented here.

** GPP index is defined as the Gross Primary Productivity (GPP) of the month divided by the maximum monthly GPP of the last 12 monthly (including the current month). It is designed to capture (with low values) times when the vegetation is undergoing drought-stress and/or is in a dormant/senesced state, both of which would indicate low live fuel moisture and a higher proportion of dead fuel and hence higher flammability.*

† Dominant type refers to a grouping of dominant tree species based on the data of Brus et al., 2012. *The dominant types used here are: "Non-native broadleaved" (Eucalyptus and Robinia), "Dry pine" (for the Mediterranean pines such as Pinus halepensis), "Conifers", and "Broadleaved", for all other conifers and broadleaved trees respectively.*

8 Input data and simulation protocol

1.1. Input data

Climate and soil

For the coupled vegetation-fire simulations we used the latest version of the DGVM LPJmL5.6 (nitrogen & tillage version). The coupled model LPJmL-SPITFIRE requires daily climate data (precipitation, radiation, temperature and relative humidity), land-use fractions, nitrogen depositions and soil texture and soil depth as input. Soil texture was derived from the Harmonized World Soil Database (HWSD) version 1.2 (Nachtergaele et al., 2012) and soil depth was set to 2m for each grid cell. Nitrogen depositions are based on the ACCMIP database (Lamarque et al., 2013), which are applied daily to the corresponding mineral N pools of the topsoil layer.

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The input climate data were taken from the data provided and described in D3.1 (see table above) while the land-use fractions were taken from D3.2, where forests, shrublands and bare soils were merged into the natural land class of the LPJmL framework.

Human development index

The Human Development Index (HDI) input data were produced by Kummu et al. (2018), who used the native 5 arc minutes resolution (0.0833°) for the generation of the ~9 km project resolution through simple averaging. Future projections (from 2015 onwards) were provided by (Perkins, O.; Millington, J.; Saxena, A.; Brown, C.; Seo, B.; & Rounsevell, 2023).

Human Population Density

Human Population density projections were adapted from the 2020-2100 1-km gridded population density estimates produced by Wang et al. (2022). The original data were downscaled to half degree and ~9km resolutions using a conservative interpolation technique (remapcon in CDO) and reformatted from .tif to .nc format using GDAL. Conservative remapping is better suited to interpolating a discontinuous data structure, as is often the case for population data. The time-continuous yearly series was generated by assuming a linear, equal-annual-increment change in the differential of the pixel value between two 5-year time steps in the original data file.

Fire Ignitions

For LPJmL-SPITFIRE simulations we used the standard lightning and human ignition probability density function approaches as described in Thonicke et al. (2010). LPJmL-SPITFIRE were enabled with multiday fires on natural land classes (natural grassland and natural forests) - an approach especially developed within the FirEUrisk project - while single-day fires occurred on managed grasslands. Fires on natural land were limited to burn for a maximum of 3 days. Daily fire duration was set to 2-5h on natural land, whereas fires on managed grassland were allowed to burn 2h maximum per day. For LPJmL-SPITFIRE-BASE (see below) simulations, only fires on natural land were allowed, where a specification of the fire duration limits is not necessary, because the BASE approach circumvents the explicit calculation of fire duration, which is not its target simulation variable.

2.1. Simulation protocol

LPJmLv5.6-SPITFIRE

For all simulations we performed a spin-up of the natural vegetation by starting the simulation from bare ground and run the model for 2500 years with reshuffled input data of the years 1960-1990. Thereafter, we conducted a 390-year land-use spin-up to bring simulated vegetation and human activity into an equilibrium state, which was the starting point for all further simulations. To evaluate model performance, we performed historic reference runs for each modelling approach (SPITFIRE and SPITFIRE-BASE, see below) using ERA5-LAND climate input data.

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Simulated burnt area of those "reference" runs were compared against GFED4s and ESACCI burnt area products between the years 2003 – 2014. Future simulations were conducted using 5 GCMs and 2 SSPs (SSP126 and SSP370, see also Table 1), running the model until 2100. To investigate the effect of future CO_2-fertilisation on plant and fuel production, we performed each set of future simulations with (a) dynamic global atmospheric CO_2 concentration (projected according to the SSP scenarios) and (b) fixed CO_2 concentration starting from 2014 until 2100. For all simulations effects of nitrogen limitation on the CO2 uptake of plants were enabled.

LPJmLv5.6-SPITFIRE-BASE

In this suite of model runs, the GLM-projected BASE model was integrated into LPJmLv5.6 model structure to replace SPITFIRE's process-based fire ignition and spread routines. Compared to the purely empirical stand-alone BASE model (when it operates without the attached DGVM and land surface model, relying entirely on gridded inputs from satellite data or projections), the variables Gross Primary Productivity (GPP), Fraction of vegetation-absorbed Photosynthetically-Active Radiation (FAPAR) and tree cover were directly simulated by LPJmLv5.6 and fed to BASE. Other fire behaviour processes computed by SPITFIRE were retained in this set of experiments.

9 Documentation of simulation results

3.1. Projected changes in future fire and vegetation

Below we summarize some of the principal projection-results using the model structures and protocols described in the preceding sections and provide some first-order interpretation of them.

Burned Area Projections: LPJmL-SPITFIRE (DGVM + SPITFIRE only)

For the DGVM-only runs, the difference between the burned area (BA) over Europe averaged over 2000-2030 compared to that averaged over 2070-2100 (hereafter referred to as 2015 and 2085, respectively), is plotted in Figure 1 for (a) SSP126 and (b) SSP370.

Figure 1a shows that the majority of Europe will experience large-scale increases in likely fire activity, mostly within the [+50 - +300%] range, by the last decades of the 21st century, while some areas will experience very extreme [>+300% BA increase) changes in fire incidence probability. We also note that many of these extreme increases occur in areas where there is relatively low fire activity at present, particularly in the foothills and lower reaches of mountain ranges and other medium-elevation areas (the Alps, Pyrenees, Massif Centrale, Sierra Nevada, Carpathian, Rhodope, Balkan and Scandinavian Ranges), which is consistent with projected fire weather in these regions, as described in D3.3. Areas that already experience significant present-day fire activity, such as Greece and the western Balkans, and much of the Iberian Peninsula, are simulated to experience limited changes in fire activity, or in some cases a decrease in BA, likely owing to climate-induced shifts in dominant vegetation coverage, as well as alterations to land-use. As it can be seen

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Figure 1b shows a similar pattern to the one shown in Figure 1a, except that potential fire activity is starkly increased across almost all of Europe, where the majority of the land surface experiences BA increases of over 300%, and the climate signal overwhelms (from BA neutral/decrease to BA increase) the bulk of the buffering effect provided by shifts in vegetation dominance in SSP126.

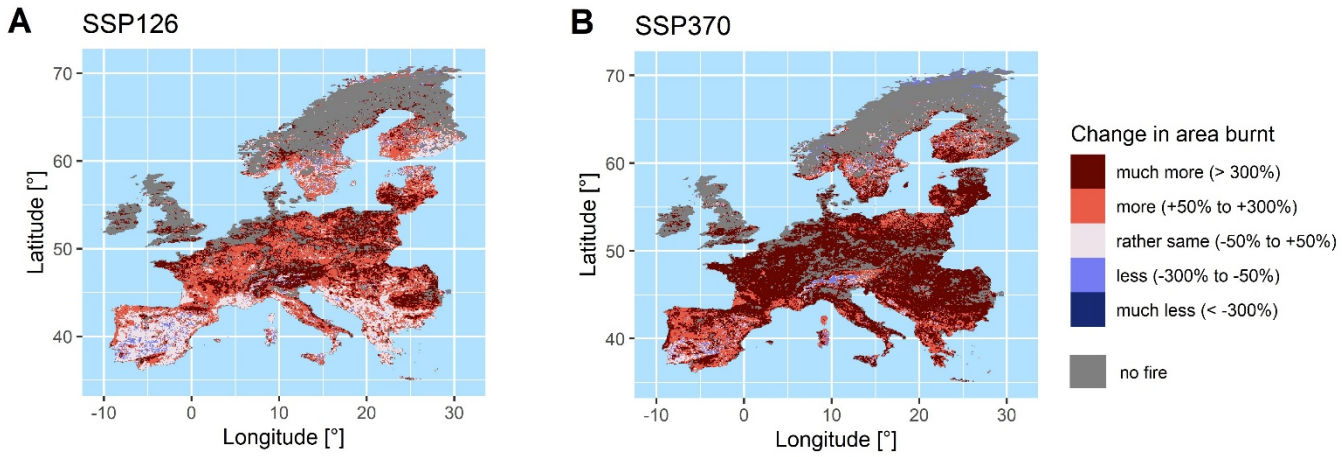


Figure 1: Relative changes in simulated burnt area between years 2000 – 2030 and 2070 – 2100 for SSP126 (panel A) and SSP370 (panel B) using LPJmL-SPITFIRE.

Burned Area Projections: LPJmL-SPITFIRE-BASE (DGVM + SPITFIRE and the BASE GLM model)

The BASE model predictions for the 2015 to 2085 burned area differentials under SSP126 and SSP370 are shown in Figures 2A and 2B, respectively. Figure 2A shows that under the low emissions scenario, fire activity is expected to decrease substantially across almost the entirety of Europe (-50% to -300% BA). This estimate is in sharp contrast to that provided by SPITFIRE, primarily because a core predictive driver of the BASE model is the human development index (HDI). The future projections of HDI all show a rise (more so in SSP126 than in SSP370), which is the one to push down fire incidence in the future scenarios (representing an increase in fire suppression/ decrease in human ignition potential, all else being equal). SPITFIRE does not currently include HDI as an input for predictive fire modelling, meaning such representation is either precluded by or implicit in its pre-existing human ignition and suppression functions, which are driven by population density - a poor proxy for HDI. Assessing the realism of either SSP126 projection estimate is beyond the scope of this technical document, however, we note the following: The GLM is driven by historical data analysis, and whether the extent of historical HDI effects on fire activity can be extrapolated to a future with substantially elevated fire risk levels is unclear. That is, there may be future conditions under which fire activity cannot be dampened by HDI-proxied socio-infrastructural investments. Indeed, this is illustrated in Fig. 2B where the slightly lower HDI in SSP370 combined with higher fire risk associated with its climate warming/drying does result in large-scale increases in fire activity in Europe, although at lower severity and spatial extent than predicted by SPITFIRE alone. In other words, whilst HDI is a strong predictor in the BASE framework and we cannot be certain of its validity in the future, the model framework does allow climate risk (i.e., FWI) to override this dampening effect of HDI.

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Thus, we surmise that, given the present-day dependency of fire activity on HDI, the BASE model provides a novel and pivotal component of European fire activity that is missing in the SPITFIRE approach. The veracity of the BASE predictions in the real world may ultimately depend on how societal development (as proxied by HDI) is translated into fire-relevant government policy intervention and investment at national and regional scale into the future.

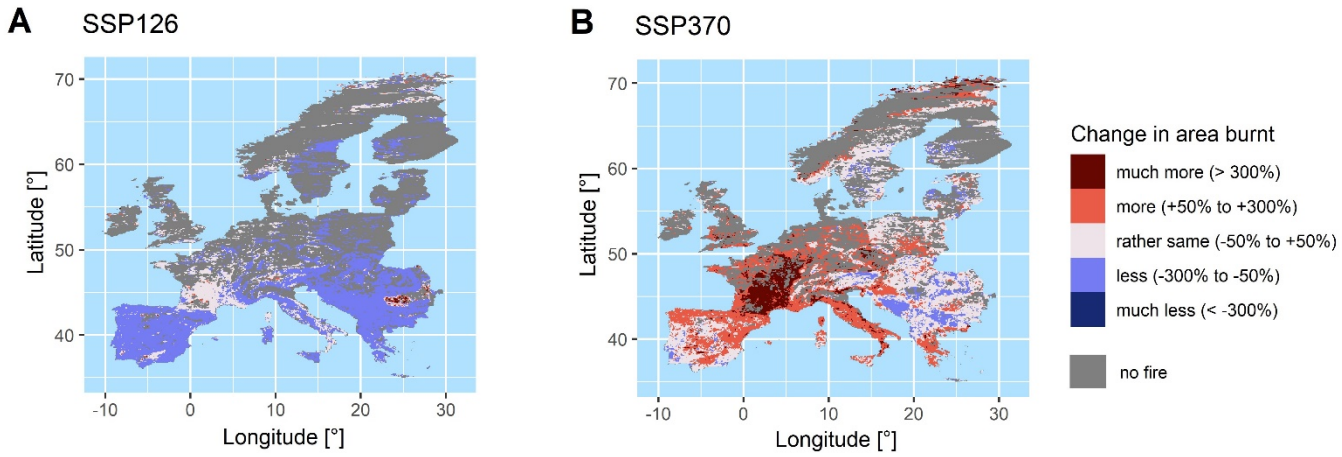


Figure 2: Relative changes in simulated burnt area between years 2000 – 2030 and 2070 – 2100 for SSP126 (panel A) and SSP370 (panel B) using LPJmL-SPITFIRE-BASE.

Vegetation Dynamics Projections: LPJmL-SPITFIRE (DGVM + SPITFIRE only)

Below we briefly discuss the projected changes in vegetation cover between 2015 and 2085 under SSPs 126 and 370, as predicted by LPJmL's DGVM, which are presented in Figures 3-5. Those vegetation changes taken from the mean of simulations that include and exclude the CO_2 fertilization effect. Vegetation dynamics are driven by climatic (e.g. temperature, precipitation, PAR), atmospheric (e.g. atmospheric CO_2 concentration) and human (e.g. land-use) changes, which may then produce changes in the spatial range of dominant vegetation types, as well as the total standing stock of carbon fixed by photosynthesis in living biomass, which is itself subject to rapid atmospheric return through fire combustion and its associated potential mortality. Under SSP126, Europe is projected to experience a near-universal large-scale loss in grassland coverage, the most severe of which represents range-shifts from grassland to forest-dominated ecosystems by the end of the century (Figs. 3A, 4A). This pattern is very likely a result of combined effects of changes in land-use, climate and related fire regimes. In some areas, this shift to forest-dominance results in an increase in the total standing stock of vegetative carbon (Fig. 5A), while in other regions, such as the Iberian Peninsula and the western Balkans, cumulative heat, moisture and fire stress reduce the total amount of photosynthetically fixed carbon on the terrestrial surface. A similar picture emerges from SSP370, however it is likely that more acute water stress reduces the proportion of grassland conversion to forest (Figs. 3B, 4B), while the simultaneous considerably elevated atmospheric CO_2 concentrations enable enhanced photosynthesis and lower mass-weighted evapotranspiration losses from the leaf surface, resulting in higher levels of vegetative carbon over much of Europe.

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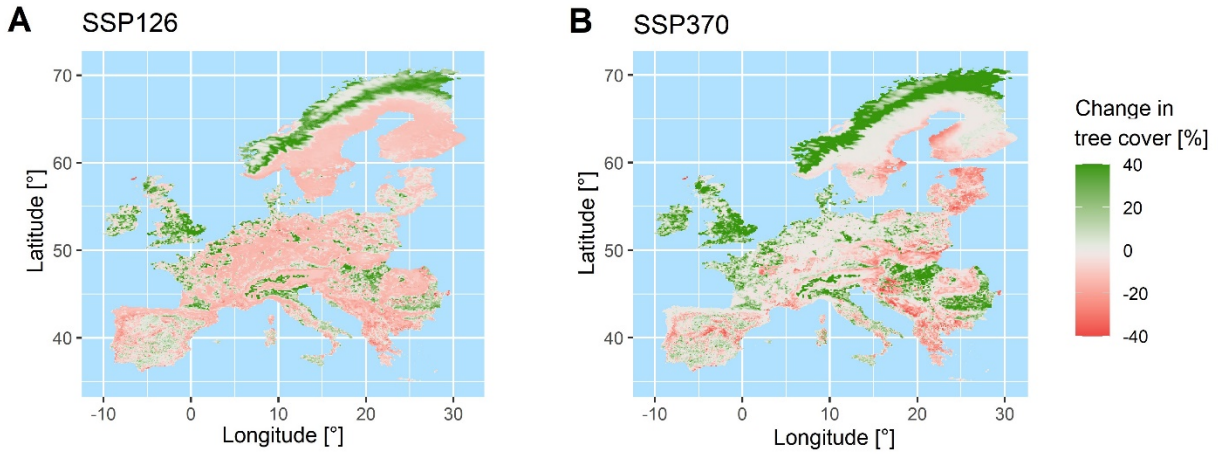


Figure 3: Relative changes in tree cover between years 2000 – 2030 and 2070 – 2100 for SSP126 (panel A) and SSP370 (panel B) using LPJmL-SPITFIRE.

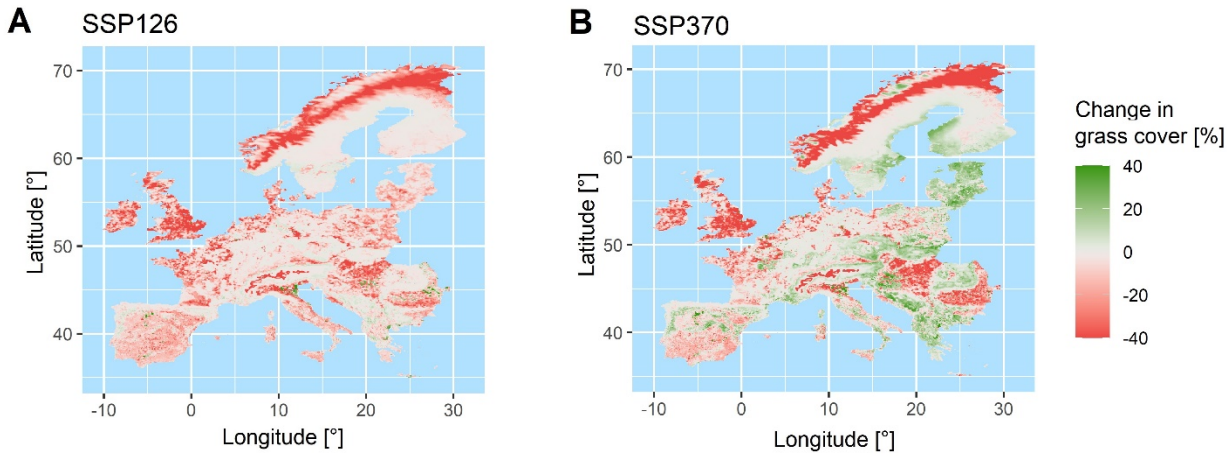


Figure 4: Relative changes in grass cover between years 2000 – 2030 and 2070 – 2100 for SSP126 (panel A) and SSP370 (panel B) using LPJmL-SPITFIRE.

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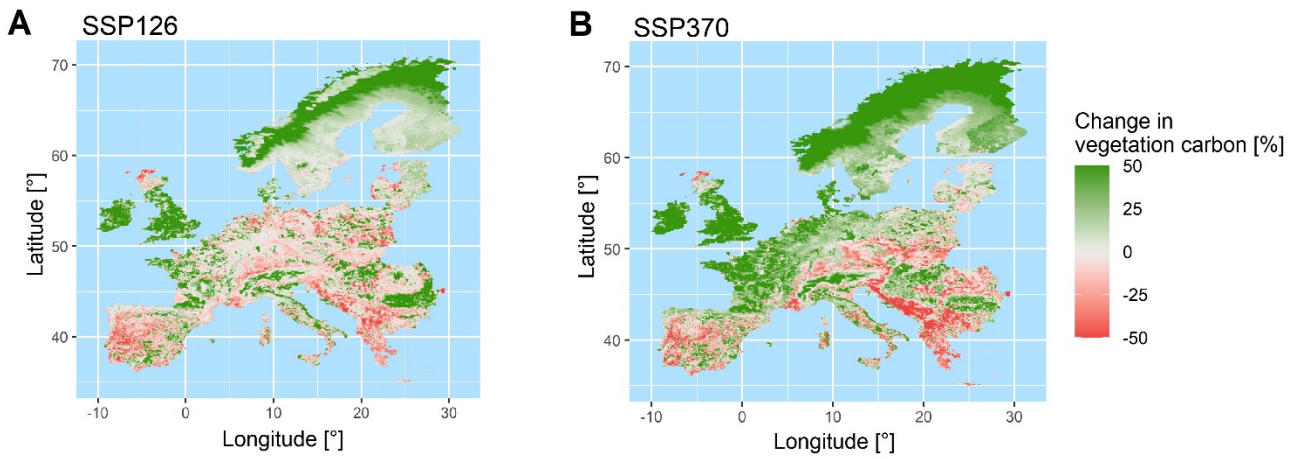


Figure 5: Relative changes in total vegetation carbon between years 2000 – 2030 and 2070 – 2100 for SSP126 (panel A) and SSP370 (panel B) using LPJmL-SPITFIRE.

4.1. Overview of variables provided in data sets

Here, we provide an overview of the variables provided in datasets, and provide a naming convention

Naming convention:	<VariableName>_<SSP>_<GCM>_<Model>.nc For instance: burntarea_ssp126_ACCESS-CM2_BASE.nc		
Description of variable	**Variable name as used in the nc-data file and additional information**	**Temporal resolution**	**Unit**
Burned area	burntarea	Monthly	Fraction of grid cell [fraction]*
Fire carbon emitted	FireC	Monthly	gC/m²
Natural vegetation cover	FPC; vegetation covers are summarized in a single file, that has 12 different bands (npft in nc-file): band 1: natural vegetation cover band 2: tropical evergreen tree band 3: tropical raingreen tree	Annual	Size of natural stand in 9 km x 9 km cell [fraction]*

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Tree cover	band 4: temperate evergreen needle-leaved tree band 5: temperate evergreen broadleaved-leaved tree band 6: temperate summergreen broad-leaved tree band 7: boreal evergreen needle-leaved tree band 8: boreal summergreen broad-leaved tree band 9: boreal summergreen needle-leaved tree band 10: C4 tropical grasses band 11: C3 temperate grasses band 12: C3 polar grasses tree cover is given by the sum of woody PFTs (band 2 to 9) grass cover is given by the sum of grass PFTs (band 10 to 12)	Annual	Fraction of natural stand in 9 km x 9 km cell [fraction]*
Grass cover		Annual	Fraction of natural stand in 9 km x 9 km cell [fraction]*
Plant Functional Type coverage		Annual	Fraction of PFTs in natural stand in 9 km x 9 km grid cell [fraction]*
Aboveground and belowground living biomass	VegC	Annual	gC/m²
Net primary productivity	NPP	Monthly	gC/m²
1-hr dead fuel	Fuel, fuel classes are combined in a single file, that has 4 different bands (fuelclass in nc-file): band 1: 1-hr dead fuel band 2: 10-hr dead fuel band 3: 100-hr dead fuel band 4: 1000-hr dead fuel	Monthly	gC/m²
10-hr dead fuel		Monthly	gC/m²
100-hr dead fuel		Monthly	gC/m²
1000-hr dead fuel		Monthly	gC/m²

*Table 3: Output variables provided in data set for LPJmLv5.6-SPITFIRE as well as LPJmLv5.6-BASE-SPITFIRE vegetation-fire models. * to convert fraction of grid cell to hectars use: fraction*(111e3*0.070313)^2*cos(latitude/180*pi)/10000*

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5.1. Description of netcdf metadata

Geographic projection of all data is: WGS84 (+proj=longlat +datum=WGS84 +no_defs)

Example of header information:

dimensions:	←	first overview of dimensions of variable: 4 dimensional: longitude, latitude, time, fuelclass, 595 longitudes, 511 latitudes, 4 fuel classes, 1212 time steps
time = UNLIMITED ; // (1212 currently)		
lon = 595 ;		
lat = 511 ;		
fuelclass = 4 ;		
variables:		
double time(time) ;	←	time dimension, variable name of time dimension is “time”
time:standard_name = "time" ;		
time:long_name = "Time" ;		
time:units = "days since 2000-1-1 0:0:0" ;		
time:calendar = "365_day" ;		
time:axis = "T" ;		
double lon(lon) ;	←	longitude dimension, name of dimension is “lon”
lon:standard_name = "longitude" ;		
lon:long_name = "Longitude" ;		
lon:units = "degrees_east" ;		
lon:axis = "X" ;		
double lat(lat) ;	←	latitude dimension, name of dimension is “lat”
lat:standard_name = "latitude" ;		
lat:long_name = "Latitude" ;		
lat:units = "degrees_north" ;		
lat:axis = "Y" ;		
double fuelclass(fuelclass) ;	←	fuel class dimension, name of dimension is “fuelclass”
fuelclass:long_name = "fuel class" ;		
fuelclass:axis = "Z" ;		
float fuel(time, fuelclass, lat, lon) ;	←	name of main variable (“fuel) and order of dimensions, if variable is read
fuel:standard_name = "fuel" ;		
fuel:long_name = "class-specific fire fuel" ;		
fuel:units = "g/m2" ;		
fuel:_FillValue = -1.e+32f ;		
fuel:missing_value = -1.e+32f ;		

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6.1. Storage and data access, how to cite

The data sets are stored in a public repository at the GFZ Potsdam, Germany. When working with the data, please cite the following:
Billing, Maik; Forrest, Matthew; von Bloh, Werner; Bowring, Simon; Hetzer, Jessica; Oberhagemann, Luke; Thonicke, Kirsten (2023): Projections of future fire and vegetation variables on European scale. GFZ Data Services. https://doi.org/10.5880/pik.2023.005

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