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The influence of thinning and prescribed burning on future forest fires in fire-prone regions of Europe

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Supplementary material for this article is available online

Abstract

Climate change is expected to increase fire risk in many forested regions, posing a potential threat to forest functioning (i.e. carbon pools and fluxes). At the same time, expansion of the wildland-urban interface threatens to bring more and more people, property, and infrastructure into contact with wildfire events. It is critical that fire be managed in a way that minimizes risk to human health and well-being and maintains forest climate change mitigation potential without affecting the important ecological role fire plays in many ecosystems. Dynamic global vegetation models (DGVMs) simulate processes over large geographic regions and long time periods and could provide information that supports fire and fuel management programs by assessing performance of such measures under different climate change scenarios in different regions. However, thus far DGVMs have not been put to this use. In this work, we introduce a novel prescribed burning (PB) module to the LPJ-GUESS DGVM. Focusing on two regions (Eastern Europe and the Iberian Peninsula), we compare the effectiveness of PB and mechanical thinning on various aspects of the fire regime under two climate change scenarios through the end of the 21st century. We find that PB and thinning, by reducing fuel load, reduce fireline intensity; this suggests that what wildfires do occur could be more easily controlled. While this would reduce risks to human health and well-being, PB comes with the tradeoff of increased fire emissions, which could contribute to respiratory problems. Mechanical thinning reduces fireline intensity by as much or more while also reducing emissions. While net primary production remained unaffected by fire management, cumulative net biome production until the end of the 21st century declined especially under the influence of thinning. While these results are based on stylized management treatments, this work shows the potential of DGVMs in exploring fire management options.

1. Introduction

Wildfires are an intrinsic feature of ecosystems all over the world and essential for many ecological processes such as rejuvenation, creation of diverse habitats or carbon turnover (Bowman *et al* 2009, Pausas and Keeley 2019). An estimated area of 360–380 Mha is burnt every year causing average emissions of ca. 2 Gt of C globally (Chuvieco *et al* 2016, Hantson *et al* 2016). Climate change is expected to substantially increase fire risks and—particularly in forests and shrublands—possibly also fire intensity in the future (Harris *et al* 2016, Dupuy *et al* 2020, Chen *et al* 2021). Some of the extremely destructive forest fires in recent years, such as in California or Australia, as well as fires observed in what would not be considered historically fire-prone regions (e.g. Siberia; (Ponomarev *et al* 2016, Chen *et al* 2021), have been linked to weather extremes that are likely to become more frequent under continued climate change (Khorshidi *et al* 2020, Bowman *et al* 2021). Even though humans actively and passively suppress fire spread in many regions, they are vulnerable to wildfire impacts, as high-intensity forest and woodland fires cause property loss, poor air quality, and deaths. If human population growth takes place in regions of high fire risk, these detrimental impacts may increase in the future, especially at the wildland-urban interface (Moritz *et al* 2014, Knorr *et al* 2016). Given that forests are an important carbon sink and are considered an important climate change mitigation measure (Pugh *et al* 2019, Smith *et al* 2020), better understanding of the impact of forest-fire management on wildfires thus is relevant not only to assess risks to humans but also for future climate change projections.

Attempting to manage wildfires in highly fire-prone regions through suppression alone is futile, as demonstrated by recurring extreme fire events in regions where suppression is practiced (Fernandes 2013, Moreira *et al* 2020). In one such region—the Mediterranean landscapes of Iberia (Spain and Portugal)—firefighting has been primarily supplemented with the construction of firebreaks in an attempt to limit fire spread and protect valuable land and infrastructure (Xanthopoulos *et al* 2006). However, recent decades have seen an intensification of the fire regime, despite increasing expenditures on firefighting, as agricultural abandonment and forestry expansion in Iberia elevated fuel loads and weakened the 'passive' firebreak effect lent by agricultural land breaking up the flammable landscape (Moreira *et al* 2020). Land managers and policymakers are increasingly realizing that integrated fire management, adapted to local natural and socio-economic conditions, likely will lead to better handling of fire as a hazard to humans while recognizing fire's important role in ecosystems (Vallejo Calzada *et al* 2018, Kelly *et al* 2020, Moreira *et al* 2020). Two fuel management techniques are commonly considered. Thinning—the removal of live trees to reduce live and, indirectly, dead fuel load—is seen as potentially co-beneficial in that felled woody biomass can return an economic gain, depending on the tree species. Prescribed burning (PB) has also been recognized as a potentially efficient measure but is controversial and in some countries illegal (Xanthopoulos *et al* 2006, Fernandes 2013, Vallejo Calzada *et al* 2018). Nevertheless, in a previous fire management simulation experiment for the whole of Europe, a stakeholder-engagement process returned PB as one of the preferences voiced by the stakeholders (Khabarov *et al* 2016).

In coupled ecosystem-fire models that are applied to investigate past or future fire regimes and their impacts on ecosystems, the role of humans is poorly described (Hantson *et al* 2016), focusing on humans' role as ignition sources and/or in slowing fire spread and thus constraining burnt area. The latter is typically represented by empirical, relatively simple algorithms (Hantson *et al* 2016). Different forest-fire management approaches such as removal of combustible material, controlled burning or creation of fire breaks, which aim to prevent uncontrollable fires and to reduce fire intensity (Martell 2015) are not captured by these models. This modelling shortage is partially because most fire-vegetation models do not simulate forests with the required structural realism, such as stem density or diameter, which facilitates the representation of fuel management. This hampers the applicability of such models to assess future fire regimes, especially the impact direct human interference on forests' fuel loads and fire spread might have.

Here, we use the dynamic global vegetation model LPJ-GUESS coupled to the fire model SIMFIRE-BLAZE (Knorr *et al* 2014, Rabin *et al* 2017), which simulates forest growth dynamics in a way that allows us to explore how forest thinning and controlled burning affect fire intensity, burn severity, and ecosystem carbon balance in two European regions.

2. Methods

2.1. Study regions

We focus on two different regions in Europe (figure 1) in which to develop our methodology and demonstrate the prospects of integrating fire management in large-scale ecosystem-fire models. One region, the Iberian Peninsula (Portugal and Spain), is fire-prone due to its warm and dry summers and flammable vegetation. In addition, land abandonment in recent decades has led to enhanced shrub and forest cover on what previously had been cropland, which had acted as fire breaks in the past (Pereira *et al* 2014, Khabarov *et al* 2016, Dupuy *et al* 2020, Moreira *et al* 2020). The Mediterranean region, of which Iberia is a part, contributes to more than four fifths of the annual area burnt in Europe (Xanthopoulos *et al* 2006, Wu *et al* 2015).

In our other region, Eastern Europe (here Bulgaria, Romania, Moldova, Ukraine, Belarus, Poland, Czech Republic, Slovakia, and Hungary), forest fires have historically been infrequent. However, some studies have indicated increasing fire danger with climate change in that region (Wu *et al* 2015, Khabarov *et al* 2016, Trnka *et al* 2021). It has been suggested that the historical rarity of large-scale burning in Eastern Europe means the region has not developed the forecasting and management techniques that are needed to prepare for a more intense future fire regime (Mitsopoulos *et al* 2017).

2.2. Vegetation and fire model

The patch-dynamic, process-based, global vegetation-ecosystem model (dynamic global vegetation model, DGVM) LPJ-GUESS is designed for regional or global simulations of vegetation dynamics and biogeochemical cycles (Hickler *et al* 2004, Smith *et al* 2014). Based on climate data, carbon dioxide concentrations of the atmosphere, nitrogen deposition, soil information, and land use, LPJ-GUESS computes vegetation structural composition and functional properties of the ecosystem. Physiological

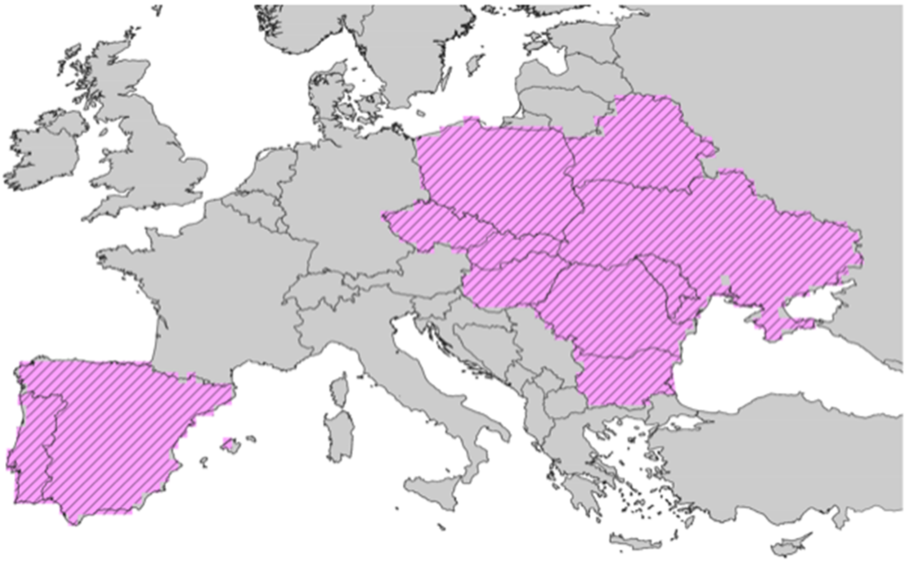

Figure 1. Map of the regions examined in this study: Iberia (left) and Eastern Europe (right).

processes such as photosynthesis, respiration, stomatal conductance, and soil water balance are simulated on a daily time step; the net primary production accumulated over a simulation year is allocated to leaves, fire roots, and sapwood based on plant functional type (PFT)-specific allometric relationships. By incorporating forest 'gap dynamics,' LPJ-GUESS explicitly represents establishment, and growth and mortality of individuals, which are grouped into age cohorts competing for space, light, water, and nitrogen. LPJ-GUESS's representation of forest demography, including explicit height and stem diameter growth, allows subgrid-scale land use dynamics like deforestation and successional forest regrowth after land abandonment or wood harvest to be captured in detail (Bayer *et al* 2021, Lindeskog *et al* 2021). The model has been successfully evaluated against a broad range of observations ranging from stand to global scale (Smith *et al* 2014, Hantson *et al* 2020, Lindeskog *et al* 2021). Vegetation in this study was represented by ten tree PFTs plus C_3 and C_4 grass PFTs, as in Smith *et al* (2014). As some aspects of forest growth dynamics are treated stochastically, for each grid location a number of replicate 'patches' are computed and their output averaged. Agricultural areas were not simulated in this experiment.

Fire is modelled by SIMFIRE-BLAZE (Rabin *et al* 2017). SIMFIRE is an empirical burned area model that was trained on global-scale data, including remotely-sensed vegetation and land cover, constraining burned-area by fire weather, fuel load and continuity, and human population density (Knorr *et al* 2014, Rabin *et al* 2017). Specifically, SIMFIRE calculates daily burned fraction based on temperature and humidity (through the Nesterov fire index, which represents fire danger), biome type (the percentage of woody PFTs), and fuel continuity (based on annual maximum fraction of vegetation-absorbed photosynthetically active radiation). In addition, burned area is reduced at higher human population densities. The BLAZE module (Rabin *et al* 2017, Nieradzik *et al* in prep.) computes fireline intensities and carbon fluxes using fuel load and fire weather parameters to estimate fuel consumption and tree mortality (Rabin *et al* 2017). BLAZE translates computed fireline intensities into tree survival probabilities depending on vegetation height (for savanna trees) or diameter at breast height (for other trees). Literature-based calculations of mortality are used for different biome types.

LPJ-GUESS with SIMFIRE-BLAZE has been shown to perform well compared to satellite observations in terms of both mean and interannual variability of global burned area (Hantson *et al* 2020). Additional details of LPJ-GUESS-SIMFIRE-BLAZE, including changes since its description in Rabin *et al* (2017), can be found in the supplement (available online at stacks.iop.org/ERL/17/055010/mmedia).

2.3. Fire management

Two different types of wildfire management by fuel load restrictions, and their combination, were compared here to wildfire in non-managed forests. A thinning treatment was introduced, based on a threshold of 20% thinning every ten years considering all woody PFTs simulated in a grid cell, adopting developments in Lindeskog *et al* (2021). Thinning removes preferentially small-diameter individuals and continues until the target intensity of fraction of harvested above ground biomass is reached. The thinned biomass is removed to prevent fuel accumulation, such that no stem or twig biomass is left as litter (rather than 5% and 25%, respectively, which is the standard setting of LPJ-GUESS).

While thinning occurs at a regular interval, PB happens whenever certain criteria are met. The aim in this implementation is to treat only patches that are at risk of highly damaging fire, but on days where fire intensity is low. BLAZE calculates potential fireline intensity and tree fire biomass loss (combustion and mortality) every day in every patch, regardless of whether fire actually occurs there. If a patch's probability of a fire with tree biomass loss greater than 20%, accumulated over a calendar year, exceeds 1%, the patch is flagged for PB. This will take place the next time the potential fireline intensity is between 3000 and 7000 kW m^{-1}—which will burn most dead fuel without too much live biomass loss—unless a non-prescribed fire occurs before then. The prescribed fire flag carries over from year to year, only being disabled upon burning.

Each gridcell contained four experimental stands: One control (no fire management; 'No FM') and three treatment stands (thinning, prescribed fire, and both). A fifth, 'natural' stand was also simulated, which SIMFIRE used to calculate gridcell fire probability; results from this stand will not be presented. The natural stand differed from the experimental stands in that the latter were cleared and re-established in 2020 (to represent newly-established managed forests), whereas the former was simulated as primary vegetation throughout the experiment.

2.4. Simulation setup

The spatial resolution of LPJ-GUESS grids cells was set to $0.5^\circ \times 0.5^\circ$, and the simulation modeled vegetation dynamic parameters for 50 replicate patches per stand. Spin-up followed the standard protocol (Smith *et al* 2014) in which the first 30 years of the historical-period climate input data are repeated for a period of 500 years at constant CO_2 and N-deposition levels, to equilibrate C and N pools in soil, litter, and vegetation. At the end of the spin-up phase, a dynamic balance of those pools is reached. Transient simulations then proceeded from the beginning of their respective climate forcings.

Two types of transient simulations were performed. The 'evaluation' simulation was designed to compare LPJ-GUESS SIMFIRE-BLAZE burned area to observed burned area from the Global Fire Emissions Database (GFED) version 4.1 s (https://daac.ornl.gov/VEGETATION/guides/fire_emissions_v4.html). This run used reanalysis climate forcings (daily mean/minimal/maximal temperature, precipitation, solar radiation, wind speed, and relative humidity) for 1901–2016 from GSWP3-W5E5, as provided by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) phase 3a (www.isimip.org/protocol/3/). ISIMIP phase 3 also provided historical nitrogen deposition and land use maps (both through 2015, with the last year being repeated for 2016), as well as population density and CO_2 concentration. To reduce computational demand, all cropland was simulated as rainfed spring wheat.

The 'experimental' simulations used historical (1850–2014) and future (2015–2100) bias-corrected climate forcing from ISIMIP phase 3b, based on the Coupled Intercomparison Model Project Phase 6 (Eyring *et al* 2016). We chose forcings from IPSL-CM6A-LR, which has been shown to result in global mean warming that lies in the mid-range of multi-model projections. Results are compared for a low and high warming scenario, in this case representative concentration pathways (RCPs) 2.6 and 8.5 (van Vuuren *et al* 2011), respectively. Atmospheric CO_2 levels are taken from CMIP6, via ISIMIP. Nitrogen deposition and population density used the same inputs as the evaluation run during the historical period but were held constant after 2014 in order to focus on impacts of the climate change scenarios. A stylized land use scenario was used to represent primary (never-managed) land cover through 2014, five years of cropland from 2015 to 2019, and finally conversion to 50% unmanaged land and 50% managed forest in 2020. The managed forest was evenly split among the four experimental stands described in section 2.3.

3. Results

Total simulated area burnt averaged over the period 2001–2016 agrees relatively well with burned area retrieved from GFED4.1 s (Randerson *et al* 2017) (figure 2), with LPJ-GUESS having similar values in Iberia and being ca. 25% below the GFED-derived area burnt in Eastern Europe. Simulated burned fraction in Iberia exceeded that in EEU by a factor of around 4–7, both for present day climate as well as under future climate (table 1), which was expected due to the larger amount of herbaceous vegetation in Iberia which fosters fire spread. Spatially, LPJ-GUESS projects maximum area burnt in the northern parts of the domain for Eastern Europe, resembling observations. In the Iberian Peninsula, LPJ-GUESS underestimates the degree of burning in Portugal and simulates maximum area burnt in western and south-eastern Spain (not shown).

Fuel combustion in burnt patches as well as fuel loads (averaged over burnt and unburnt patches) in eastern Europe (EEU) notably exceeded values simulated in Iberia (factor *ca.* 2–3) under both warming scenarios, corresponding to the higher vegetation biomass in EEU (figure 3) with its cooler climate and vegetation dominated by temperate mixed forests rather than evergreen forests, woodlands, and shrublands. Thinning (Thin) decreased fuel load and, particularly, combustion both in Iberia and in EEU compared to No FM. PB decreased fuel load, although less so in Eastern Europe than Iberia. However, PB

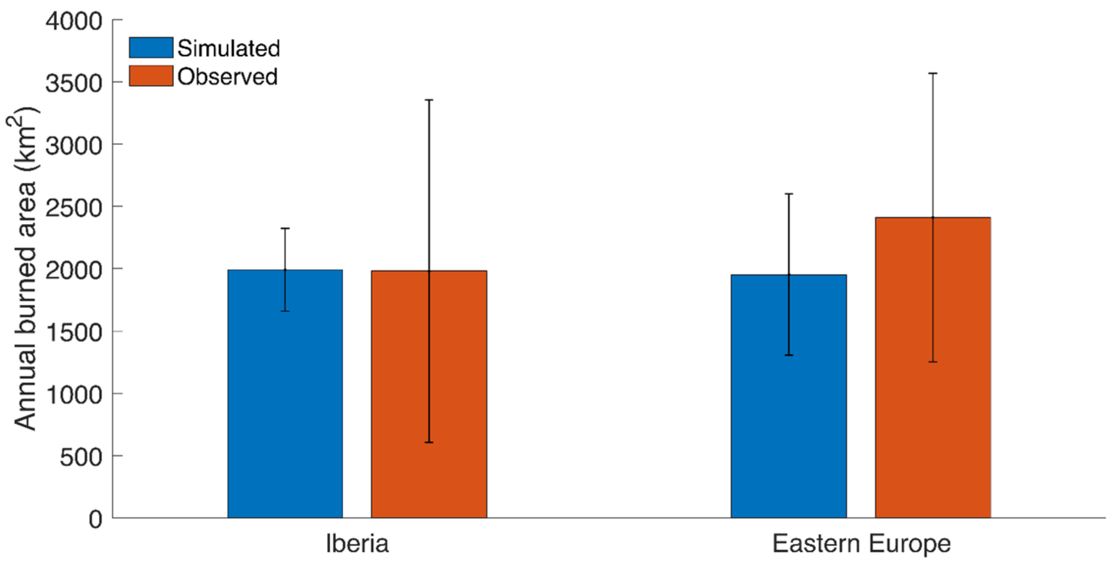

Figure 2. Observed GFED4.1 s and simulated mean and standard deviation (km^2) in Iberia (a) and eastern Europe (b) for the period 2001–2016. Fires on croplands (as designated by the MODIS MCD12 IGBP land cover product's IGBP 'cropland' classification (Friedl *et al* 2010), Yang Chen, pers. comm., 2020) are excluded from GFED to allow comparison with LPJ-GUESS, as SIMFIRE does not simulate agricultural burning (Knorr *et al* 2014).

increased fuel combustion relative to No FM in Iberia and led to more or less similar values compared to No FM in EEU. This can be attributed to PB increasing fire occurrence in relatively moist, high-biomass patches. Thin + PB had the lowest fuel load of all treatments, but this did not always translate into the lowest fuel combustion—indeed, it had higher combustion than even the No FM treatment in Iberia. Fuel combustion was closely tied to fire emissions, which are shown in table 1, which shows units of carbon combusted. In fire emission partitioning schemes commonly used in global vegetation-fire models (e.g. Andreae and Merlet 2001, Li *et al* 2012), these values would correspond linearly with emissions of species impacting human health, such as aerosol particles or tropospheric ozone precursor substances (Knorr *et al* 2017).

Mean fireline intensity (figure 4) in eastern Europe was found to be more than double that in Iberia under both climate change scenarios, reflecting the larger fuel load available for combustion. In both regions, RCP2.6 had lower mean fireline intensity than RCP8.5. All treatments lowered fireline intensity in both regions and scenarios; the reduction was greatest when both fire management options were combined, but in this case the difference between RCP2.6 and RCP8.5 was small.

Mechanical thinning and the combined fire management reduced vegetation and total ecosystem carbon pools (figure 3, table 1) when compared to No FM. Fire management affected the carbon balance over the 21st century in that thinning and PB resulted in considerably less cumulative net carbon uptake (net biome productivity, NBP: net primary productivity minus heterotrophic respiration, emissions from disturbance, and emissions from harvested material, including the long-lived product pool) in both EEU and Iberia (figure 5). In all four scenarios, the No FM simulation resulted in the largest cumulative uptake, but the difference between no FM and PB was very small in EEU. In both regions in the RCP 8.5 scenarios, ecosystems turned into a carbon source from around ca. 2080, irrespective of fire management—a climate-change driven response. The sink strength overall in Iberia was ca. 50% lower than in EEU.

The lower cumulative NBP in the thinning treatments was not primarily due to a reduction of NPP (table 1), which was either only slightly reduced or even slightly enhanced. The reduction in NPP is small because small-diameter trees being selected as well as somewhat enhanced light transfer into the canopy. Moreover, removing individuals reduces competition for nitrogen, which can enhance photosynthesis. Heterotrophic respiration was also not much affected (not shown). The chief reason for lower overall net carbon storage lies in thinning-related harvest fluxes, which are included in the NBP calculations. As a default, about two-thirds of woody biomass removed from a forest is assumed to be oxidized the same year after harvest, and the remainder is transferred into a product pool that decays at 4% per year (Lindeskog *et al* 2021). These assumptions are highly uncertain, and using more wood from thinning treatments for long-term products could result in potentially quite different overall carbon balance impacts.

Table 1. Overview of fire- and ecosystem-related variables for eastern Europe (EEU) and Iberia (IBE) and the two RCPs for the four different treatments. Values are given as averages (dark colour) and standard error (light colour) for the period 2080–2100.

		Mean fuel load (kgC m^{-2})		Mean annual dead fuel combustion (kgC m^{-2})		Mean annual fireline intensity (kW m^{-1})		Mean annual burned area (%)		Mean annual fire emissions (kgC m^{-2} y^{-1})		Mean annual total C (kgC m^{-2})		Mean annual live plant C (kgC m^{-2})		Mean annual NPP (kgC m^{-2})	
	RCP	IBE	EEU	IBE	EEU	IBE	EEU	IBE	EEU	IBE	EEU	IBE	EEU	IBE	EEU	IBE	EEU
No FM	2.6	1.22	3.18	0.74	2.68	12 515	31 765	1.00	0.23	0.81	3.25	13.81	18.12	3.92	6.99	0.40	0.57
		0.02	0.02	0.02	0.05	752	2057	0.06	0.01	0.02	0.07	0.03	0.07	0.03	0.07	0.03	0.02
	8.5	1.23	2.68	0.78	2.41	21 934	59 355	2.20	0.33	0.86	3.11	12.69	17.32	2.92	6.66	0.37	0.53
		0.04	0.02	0.03	0.03	1484	2583	0.18	0.01	0.03	0.04	0.08	0.04	0.08	0.02	0.05	0.02
Prescribed burning	2.6	0.95	3.15	1.14	2.61	5830	22 421	2.00	0.33	1.19	1.93	13.70	18.08	3.87	6.96	0.40	0.57
		0.02	0.02	0.04	0.04	485	1899	0.16	0.02	0.04	0.05	0.03	0.07	0.03	0.07	0.03	0.02
	8.5	1.01	2.57	1.03	2.20	9771	20 537	4.24	0.90	1.04	2.46	12.61	17.26	2.91	6.63	0.37	0.52
		0.04	0.02	0.04	0.04	602	1640	0.45	0.07	0.04	0.05	0.08	0.05	0.08	0.02	0.05	0.02
Thinning	2.6	0.81	1.83	0.56	1.63	6132	13 517	0.87	0.22	0.60	1.80	12.81	16.51	2.97	5.79	0.42	0.56
		0.01	0.01	0.02	0.04	502	989	0.05	0.01	0.02	0.05	0.04	0.07	0.04	0.07	0.03	0.02
	8.5	0.85	1.49	0.59	1.55	11 284	25 367	1.90	0.31	0.66	1.81	12.21	15.89	2.54	5.66	0.39	0.51
		0.02	0.02	0.02	0.03	623	1160	0.17	0.01	0.02	0.03	0.05	0.07	0.06	0.05	0.04	0.02
Thinning and prescribed burning	2.6	0.70	1.8	0.99	1.79	4262	11 074	1.53	0.27	1.03	0.01	12.74	16.48	2.95	5.78	0.42	0.55
		0.01	0.01	0.04	0.04	165	806	0.11	0.00	0.04	0.04	0.04	0.07	0.03	0.07	0.03	0.01
	585	0.69	1.42	0.89	1.76	5224	13 096	3.66	0.60	0.87	1.88	12.14	15.85	2.53	5.66	0.39	0.51
		0.02	0.02	0.04	0.04	188	734	0.41	0.03	0.04	0.00	0.05	0.04	0.06	0.06	0.04	0.02

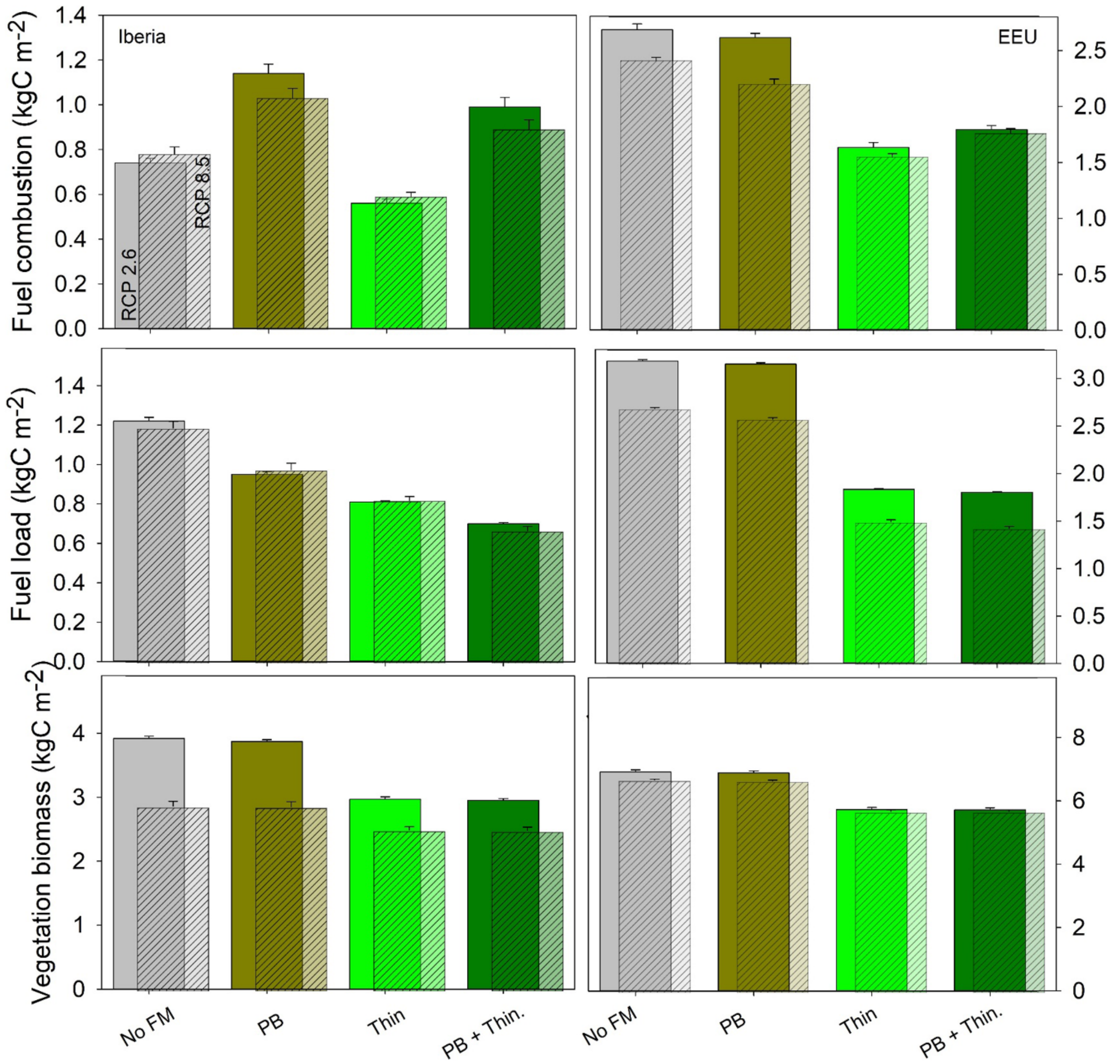

Figure 3. Simulated dead fuel combusted, mean fuel load at the end of the year, and vegetation carbon averaged over the period 2080–2100 in Iberia and Eastern Europe under RCP 2.6 (filled bars) and 8.5 (shaded bars). No FM: no fire management in simulated vegetation; PB: prescribed burning; Thin: thinning. Note the different *y*-axes scales for EEU and Iberia.

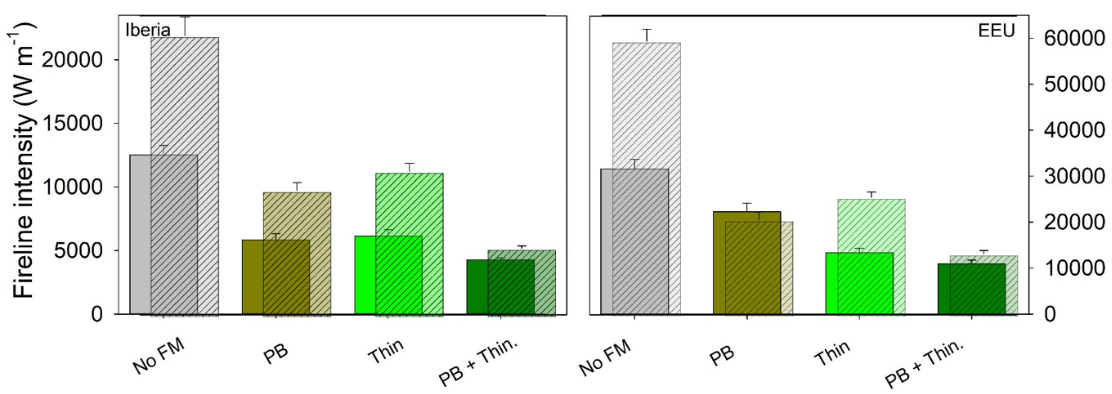

Figure 4. Mean annual fireline intensity in kW m^{-1} for each management averaged over the period 2080–2100 in Iberia and Eastern Europe under RCP 2.6 (filled bars) and 8.5 (shaded bars). Abbreviations as in figure 2. Note the different *y*-axis scales.

4. Discussion

While thinning did not affect (or slightly reduced) burned area, treatments with PB had higher burned area than the control; this effect was mitigated somewhat when combined with thinning (table 1). However, burned area *per se* is not necessarily representative of fire risk and impacts. Risk to property and

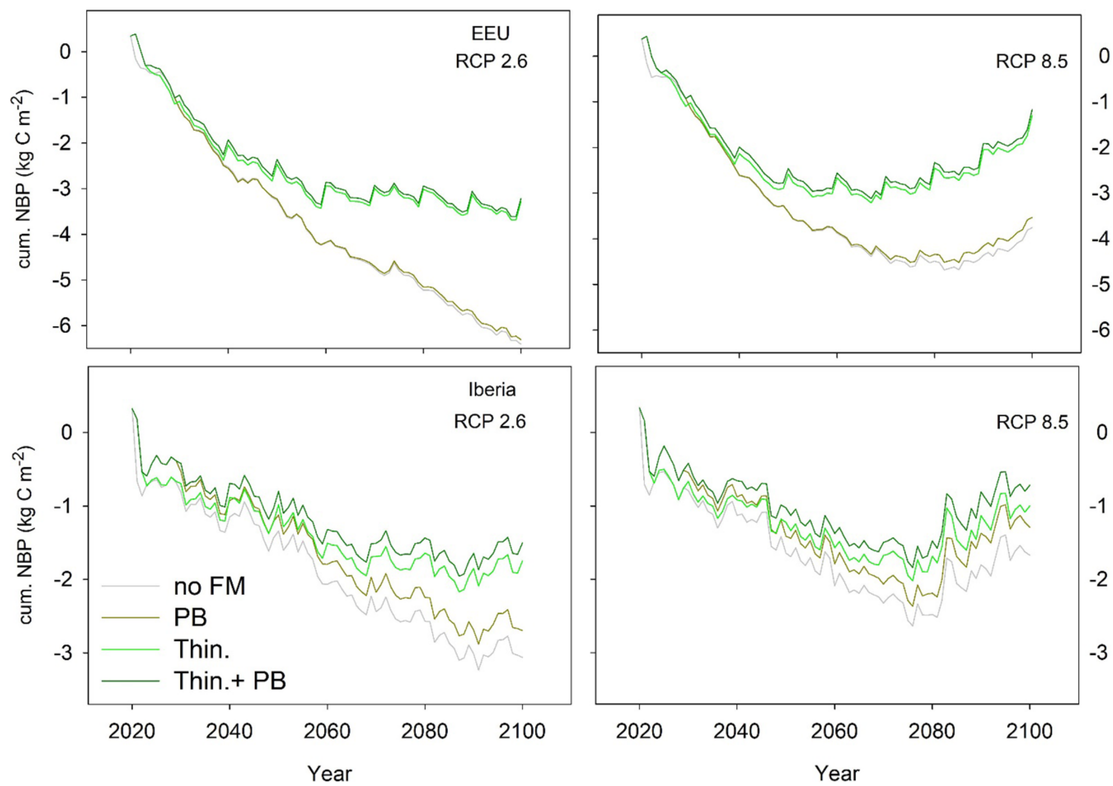

Figure 5. Cumulative carbon balance (net biome productivity, NBP) for Iberia and Eastern Europe over the simulation period. Negative indicates carbon sink.

impacts on ecosystem structure are mediated by fire intensity (Fernandes 2013), which both thinning and PB achieved. Thus, prescribed fire means more land burns, but those fires are less severe and more easily controlled.

It is worth noting, however, that the implementation of PB in LPJ-GUESS—while novel for a DGVM—represents a sort of crude maximalist approach. The LPJ-GUESS/BLAZE code structure only allows patches to either burn completely or not at all; prescribed fire is thus applied to entire patches. In the real world, land managers can use prescribed burns selectively to break up flammable areas into unburned (flammable) and burned (nonflammable) patches, with the aim of preventing any wildfires from spreading too far. Such techniques mean that PB actually can reduce burned area in some regions, including the Mediterranean (Corona *et al* 2015).

The greatest reduction of fire intensity was seen in the combined Thin + PB treatment, which supports the notion that a combination of different measures is likely to be more successful as a fire-risk mitigation measure than single options by themselves (Fernandes 2013, Kalies and Yocom Kent 2016). Reduced fire intensities have also been observed in controlled experiments in response to either thinning, PB, or both—both in fire prone regions in Europe and the US ((see e.g. Fernandes 2013, Kalies and Yocom Kent 2016) and references therein).

In addition to affecting fuel load, thinning can also affect fuel moisture. By reducing evapotranspiration and plant competition for soil water, thinning can increase both live and dead fuel moisture (Corona *et al* 2015). On the other hand, the resulting more-open forests may also be sunnier, warmer, and windier, thus increasing evapotranspiration and decreasing fuel moisture (Kalies and Yocom Kent 2016). Observations as well as modelling results indicate that these microclimatic changes can enhance fire severity (Kalies and Yocom Kent 2016, Parsons *et al* 2018). LPJ-GUESS with SIMFIRE-BLAZE does not capture either of these effects directly; live and dead fuel moisture is not explicitly modeled but rather depends on the Nesterov Index (a cumulative function of daily temperature and dew point since last rainfall). Thinning-fire interactions overall are poorly understood; impacts on fire spread and intensity may depend on local conditions and how much the forest is opened up.

In addition to the risk to people, property, and infrastructure from fires themselves, burning also affects human health through the emission of pollutants such as aerosols and toxic gases that negatively affect the respiratory and cardiovascular systems (Finlay *et al* 2012). Using total emitted C as a proxy for all harmful pollutants, we found that thinning alone reduced fire emissions while PB increased them (although, as with burned area, this effect was somewhat reduced when paired with thinning). Along with concerns about prescribed fires getting out of hand, particulate pollution contributes to lower acceptance of PB as a fire management measure among the local public (Buizer and Kurz 2016). This suggests that—at least in proximity to human settlements—thinning may be the preferable management as it reduces risk of intense fires, with health co-benefits.

Because of their carbon uptake from the atmosphere and potentially relatively long-term storage in woody biomass and soils, forests are increasingly seen an important component of climate change mitigation strategies and scenarios (Smith *et al* 2020). Increasing frequency and/or severity of wildfires poses a risk to such a strategy, as ecosystems can transition to lower-carbon states (Anderegg *et al* 2020). Although fuel management techniques might reduce carbon stocks in the short term, long-term sequestration can increase due to avoided future burning (Campbell and Ager 2013). In our simulations, PB reduced cumulative NBP only slightly compared to the No FM experiment; this is similar to what was found in some previous modelling work (Campbell and Ager 2013, Volkova *et al* 2021), although uncertainties in the responses of carbon fluxes to PB are large (Hunter and Robles 2020). The thinning and combined treatments reduced sink strength much more, highlighting the importance of using wood removed from forests for long-term carbon products—if less of the removed wood oxidized rapidly, the impacts on NBP would be much more favorable. Overall, the potential of fuel management to maintain both carbon pools and sink fluxes likely depends on the degree of climate change, forest type, and age and degree of management interference.

In summary, because fire risk will increase under climate change in many regions, there is a clear need for effective wildfire management strategies. Fire will be increasingly a threat not only to human property and health; as forests become more prominent as mitigation measures, the assessment of the success of fire management measures in different forest types and climates need to also include how these interact with the forest's carbon uptake and storage. By using a global-scale model that operates on relatively coarse spatial resolution, the results we present here are 'broad brush' and cannot reflect nuanced variations that depend on local factors such as culture and historical land use (e.g. grazing in forested landscapes reduces flammable fuel), topography (e.g. fire management in mountains may differ from practices in flat landscapes), and economy (e.g. some fire management practices are much more expensive than others; Xanthopoulos *et al* 2006). Still, incorporating fuel management strategies into fire-enabled DGVMs has the advantage that these models can explore the processes that link fuel management, vegetation structure and fire intensity and can thus be applied to a broad range of different climate change scenarios. Moreover, we can explore impacts consistently and assess synergies and trade-offs that might exist between fire management, risk to property, health, and climate change mitigation.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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