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Forest fires and adaptation options in Europe

**Nikolay Khabarov · Andrey Krasovskii · Michael Obersteiner ·
Rob Swart · Alessandro Dosio · Jesús San-Miguel-Ayanz ·
Tracy Durrant · Andrea Camia · Mirco Migliavacca**

Abstract This paper presents a quantitative assessment of adaptation options in the context of forest fires in Europe under projected climate change. A standalone fire model (SFM) based on a state-of-the-art large-scale forest fire modelling algorithm is used to explore fuel removal through prescribed burnings and improved fire suppression as adaptation options. The climate change projections are provided by three climate models reflecting the SRES A2 scenario. The SFM's modelled burned areas for selected test countries in Europe show satisfying agreement with observed data coming from two different sources (European Forest Fire Information System and Global Fire Emissions Database). Our estimation of the potential increase in burned areas in Europe under "no adaptation" scenario is about 200 % by 2090 (compared with 2000–2008). The application of prescribed burnings has the potential to keep that increase below 50 %. Improvements in fire suppression might reduce this impact even further, e.g. boosting the probability of putting out a fire within a day by 10 % would result in about a 30 % decrease in annual burned areas. By taking more adaptation options into consideration, such as using agricultural fields as fire breaks, behavioural changes, and long-term options, burned areas can be potentially reduced further than projected in our analysis.

Keywords Forest fires · Europe · Adaptation · Climate change

Introduction and background

Adaptation to climate change becomes increasingly important for the scientific community and decision-makers. With respect to forest fires, the impacts of warmer and drier weather observed in the past are expected to become stronger in the future under projected climate change (Pechony and Shindell 2010; Rego et al. 2010; Schelhaas et al. 2010; San-Miguel-Ayanz et al. 2013b). Fires are one of the main disturbances that affect terrestrial ecosystems and have profound consequences on global climate, air quality, and vegetation structure and functioning (Bowman et al. 2009; Marlier et al. 2012). In Europe alone, fires impact more than half a million hectares of forest every year. Although fire is required for the natural seeding of plant species in some (e.g. Mediterranean) ecosystems (Vélez 1990), the aggregate consequences of large-scale destruction are overwhelmingly negative: fires devastate the carbon storage of forests and can lead to large economic damages and loss of life (San-Miguel-Ayanz and Camia 2010).

Fire regimes are determined by climate, vegetation, and direct human influence. Climate is recognized as the major determinant of fire patterns on a global scale (Marlon et al.

N. Khabarov (✉) · A. Krasovskii · M. Obersteiner
International Institute for Applied Systems Analysis,
Schlossplatz 1, 2361 Laxenburg, Austria
e-mail: khabarov@iiasa.ac.at

R. Swart
Alterra, Wageningen University and Research Centre,
Droevendaalsesteeg 3a, Building 100, 6708 PB Wageningen,
The Netherlands

A. Dosio · J. San-Miguel-Ayanz · T. Durrant · A. Camia
Institute for Environment and Sustainability, European
Commission – Joint Research Centre, Via Fermi 2749,
21027 Ispra, Italy

M. Migliavacca
Max Planck Institute for Biogeochemistry, Hans-Knöll-Str. 10,
07745 Jena, Germany

2008). In Europe, human activities including negligence and arson cause more than 95 % of European forest fires (Ganteaume et al. 2012; San-Miguel-Ayanz et al. 2012). At the same time, overall trends are closely linked to weather conditions (Rogelj et al. 2012), and climatic, socio-economic, and landscape fire drivers should be considered together to better understand inter-annual variations in burned areas (Costa et al. 2010).

A substantial decrease in summer precipitation (up to 70 %) is projected for 2070–2099 in some areas of southern Europe, increasing the frequency and severity of forest fires (Alcamo et al. 2007). In the other parts of Europe, the fire risk is also likely to increase (Alcamo et al. 2007). Active forest and fire management practices can counteract the impacts of a changing climate to some extent. An analysis of the fire risk management options in European forestry at national level shows that an increase in harvest level can stop the current build-up of growing stock and possibly decrease forest vulnerability through the reduction in old and susceptible stands (Schelhaas et al. 2010). Changing species from conifers to broadleaves might be also a viable option in the long run (Schelhaas et al. 2010). Other analyses show that the creation of agricultural fields in marginal areas is one of the most promising strategies to mitigate the effects of climate change on fire regimes, as agricultural fields can act as fire breaks preventing the spread of fire and hence reducing burned area (Lloret et al. 2002; Loepfe et al. 2002). In Mediterranean areas, enhancement of fire-fighting capacities and lowering the fuel load are found to be promising adaptation strategies for reducing fire spread, ultimately leading to consistent reductions in burned areas (Lloret et al. 2002). Nevertheless, no realistic management strategy is found to offset totally the effect of climate change (Loepfe et al. 2012), and other assessments of fire management strategies suggest that suppression and prescribed fire policies can effect only a small reduction in the total burned area (Piñol et al. 2007). Even though fire prevention measures together with improvements in fire-fighting capacity can help fire management, there are no conclusive results on how they support the reduction in extreme fire events in the Mediterranean region (San-Miguel-Ayanz et al. 2013a)

The present study is designed to explore the impact of adaptation options with regard to forest fires in Europe under projected climate change reflecting the SRES A2 scenario (Nakicenovic and Swart 2000) of the Intergovernmental Panel on Climate Change (IPCC). The main aims of our study are: (1) to quantify the potential impacts of climate change on burned area in Europe under "no adaptation" scenario and compare the results with existing literature and (2) to extend that assessment with quantitative estimation of the potential effectiveness of different

adaptation measures at pan-European scale. Among the different adaptation options, we test fuel removal via prescribed burnings and enhancement of fire suppression. These options were developed in consultation with relevant stakeholders, who provided essential inputs to the research.

Methods

Impact assessment

As a basis for modelling the potential impact of climate change on burned area in Europe, we employed a widely used terrestrial biosphere model Community Land Model (CLM) (Levis et al. 2004; Stöckli et al. 2008). The model uses a process-based fire parameterization algorithm that was specifically developed for dynamic global vegetation models (Arora and Boer 2005) and was later modified and integrated as a module within CLM (Kloster et al. 2010). Thusly augmented, CLM was used to estimate climate impact on fires on a global scale (Kloster et al. 2012), and later was refined and parameterized for the application over Europe evolving to the CLM-AB model (Migliavacca et al. 2013). CLM-AB includes both climatic and socio-economic drivers of forest fires, allowing for the implementation of adaptation strategies in the model code. This model was selected because it is able to capture the complex interactions among burned area, climate, and fuel variability in Europe (Migliavacca et al. 2013). One drawback of CLM-AB is a systematic overestimation of burned areas (Migliavacca et al. 2013), and a practical consideration is its significant computational resource requirements. For these reasons, we developed for this study a standalone fire model (subsequently: SFM). This version of the CLM-AB fire module is fully decoupled from CLM and is calibrated using a different approach.

Modelling strategy

Although the SFM model is derived from CLM-AB, it uses only datasets fully independent of CLM-AB (weather, biomass, population density) and makes its own fuel moisture computation from the ground up based on the Canadian fine fuel moisture code (FFMC) index (Van Wagner and Pickett 1985). In SFM, we also implemented a procedure for calibration of suppression efficiency which differs from CLM-AB.

Suppression efficiency depends on a number of factors, including local regulations and available resources, and varies from one country to another. In SFM as well as in CLM-AB fire module (Arora and Boer 2005), the efficiency of fire suppression is defined as the probability q of putting out a fire on a given day. Potential area burned

within 1 day and also cumulative burned area over any time period can be represented as

$$A(q) = a(1 - q)(2 - q)/q^2, \tag{1}$$

where the coefficient a reflects availability of fuel, ignition sources, and weather conditions, but is not a function of q (Arora and Boer 2005; Kloster et al. 2010). In our calibration procedure, we find a value of the variable $q = q_c$ such that $A(q_c) = A_{obs}$, where A_{obs} is the observed cumulative burned area in a specific country over a given time period. Based on a non-calibrated model run with an arbitrary value of $q = q_0$ $(0 < q_0 < 1)$ delivering accumulated burned area $A(q_0)$ for a time period for a given country, the calibrated value q_c is defined by the following equation:

$$q_c = \frac{-3 + \sqrt{8\beta + 1}}{2(\beta - 1)},$$

where $\beta = \dfrac{A_{obs}}{A(q_0)}(1 - q_0)(2 - q_0)/q_0^2.$ \hfill (2)

The value of parameter β apparently equals A_{obs}/a, and therefore, the calibrated value of suppression efficiency q_c does not depend on the arbitrary selected value q_0. The calibration method defined in Eq. (2) is rather straightforward as it requires only information on observed cumulative burned area and one test run of a non-calibrated model. We apply the country-level calibration procedure described above forcing the model to fit the reported total accumulated burned area over a time period of several years, which is long enough relative to the model's operating daily time step. An even more advanced spatially explicit (pixel level) calibration of q did not add any substantial improvements to the accuracy of modelling of country-level aggregated annual burned areas. The calibration procedure we suggested above allows for resolving the problem of modelled burned area systematically overestimating the observations reported for CLM-AB (Migliavacca et al. 2013). The approach used for calibration in CLM-AB (Migliavacca et al. 2013) is based on a different method employing the mean fire suppression time reported in the European Fire Database (EFDB) developed in the context of the European Forest Fire Information System (EFFIS) (San-Miguel-Ayanz et al. 2013b).

Input data and set-up

The SFM model uses the global dataset of meteorological forcing, subsequently referred to as the Princeton dataset[1] (Sheffield et al. 2006), which has a spatial resolution of 1 arc degree, and for the time span of 1948–2008 provides historical daily values of temperature, precipitation, wind,

specific humidity, and surface pressure. Relative humidity, which is needed for the moisture calculation implemented through FFMC (Van Wagner and Pickett 1985), was derived from temperature, specific humidity, and surface pressure by utilizing saturation vapour pressure approximation (Flatau et al. 1992).

With SFM, we investigated possible impacts of climate change and respective adaptation options based on projections provided by different Global Climate Models (GCMs) reflecting the SRES A2 scenario (Nakicenovic and Swart 2000) of the IPCC. We selected A2, a high emissions scenario, because it allows us to analyse relatively large projected climate changes. For the period 2090–2099, A2 falls between newer IPCC scenarios (Moss et al. 2010) RCP6 and RCP8.5 (Rogelj et al. 2012). For the sake of brevity, we present SRES A2 related results for three GCMs: MRI-CGCM2.3.2 (Meteorological Research Institute, Japan), CNRM-CM3 (Météo-France/Centre National de Recherches Météorologiques, France), and CSIRO-Mk3.0 (CSIRO Atmospheric Research, Australia), all part of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007). We used historical daily data from the Princeton dataset to estimate in a simplified way future daily values based on changes in mean monthly temperature and mean monthly precipitation coming from GCMs for the three future periods 2026–2035, 2046–2055, and 2086–2095 and relative to the historical baseline 1961–1970 (Strzepek 2012a, b). Changes in mean monthly temperature are added to each day's value to estimate future daily temperatures. Relative changes in monthly precipitation are used to multiply historical values to project future daily precipitation. This simplified approach for modelling future daily weather has several limitations, including the same number of "wet" days per month as in the historical period, and unchanged values for wind speed and relative humidity.

We used the dead wood and litter carbon data from the Global Forest Biomass map (Kindermann et al. 2008)—a half degree global spatial dataset. The use of a static biomass data is one of the simplifications of the SFM's modelling approach; a dynamic modelling of biomass with reasonable accuracy could help to refine the results of this analysis. In SFM, we make another simplification with the exclusion of lightning as a non-anthropogenic source of ignition. This simplification is justified because ignition potential due to high population density entirely overrules non-anthropogenic causes in Europe, where only 5 % of wildfires are sparked by lightning (Catry et al. 2010).

The SFM model is calibrated as described above over a nine-year period 2000–2008 using burned area statistics reported in EFFIS (San-Miguel-Ayanz et al. 2013b) and, as an alternative for comparison, the Global Fires Emissions

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[1] http://hydrology.princeton.edu/data.pgf.php.

Database (GFED) version 3 (Giglio et al. 2010; Van der Werf et al. 2010). These are different products in terms of spatial extent (regional vs. global), and methods for data acquisition, processing, and validation. As the population density dataset, we used GPW version 3 (CIESIN 2005).

Adaptation strategies

A number of options are available to reduce the fire risk associated with anticipated climate change. In addition to improvements in active fire suppression, there is also a range of preventive strategies such as prescribed burnings (Silva et al. 2010), management options aimed at restricting the potential spread of fire (e.g. utilizing agricultural fields as fire breaks) (Lloret et al. 2002), and long-term options that include increase in rotation length and change of tree species (Schelhaas et al. 2010). Various combinations of reactive and preventive measures can also be pursued to reduce risk, improve flexibility, and optimize the use of available resources.

This study is focused on a subset of available options, namely: active suppression and fuel removal by prescribed burnings. These specific adaptations are applicable on regional and continental scales and were identified in dialogue with the experts and stakeholders in the field of fire management and forest sector.[2] The SFM model is designed to evaluate those adaptation options on a continental scale, quantifying their potential impact under selected climate change scenarios.

Prescribed burnings in SFM were simulated by explicitly reducing available fuel biomass as a consequence of planned preventive fires. Following the CLM-AB's fuel representation approach (Migliavacca et al. 2013), we defined fuel available for burning as a combination of litter and coarse woody debris (CWD) pools, excluding stem biomass and shrub and grass components. As an estimate of the degree of fuel reduction induced by prescribed burnings, we used the values of 50 % for both litter and CWD pools as suggested for needle leaf trees (Kloster et al. 2010). Because the values for broadleaf trees are higher (60 %), our approach is rather conservative.

We model potential improvements in fire suppression through modification of the parameter q (Eq. 1). There are certain limitations on the use of q as a proxy for the suppression capacity, mainly resulting in difficulties in disentangling detection and response components, and other related factors; e.g. setting up fire breaks. As an implication, the current version of the fire module only allows for sensitivity analysis of the aggregated proxy variable

q rather than of more explicit indicators. Nevertheless, this approach provides a quantification of impacts of reactive and preventive adaptation strategies at a large scale within a single modelling framework.

Additional options for risk reduction are excluded from the analysis. The fire algorithm of CLM-AB (Arora and Boer 2005), designed for large-scale applications, is not able to catch such local details as agricultural fields serving as fire breaks. Similarly, transition to fire-resistant tree species cannot be handled adequately because the model employs a simplified representation of fuel which does not distinguish among species (and also does not explicitly account for shrub and grass fuel components). Behavioural aspects, though important, are difficult to capture in this type of model and are therefore also excluded.

Results and discussion

Yearly forest fire dynamics during the historical period

By construction, the SFM calibration procedure guarantees exact agreement between simulated and reported cumulative country-level burned areas over the entire historical nine-year period 2000–2008. However, the model describes reasonably well the inter-annual variability of burned areas.
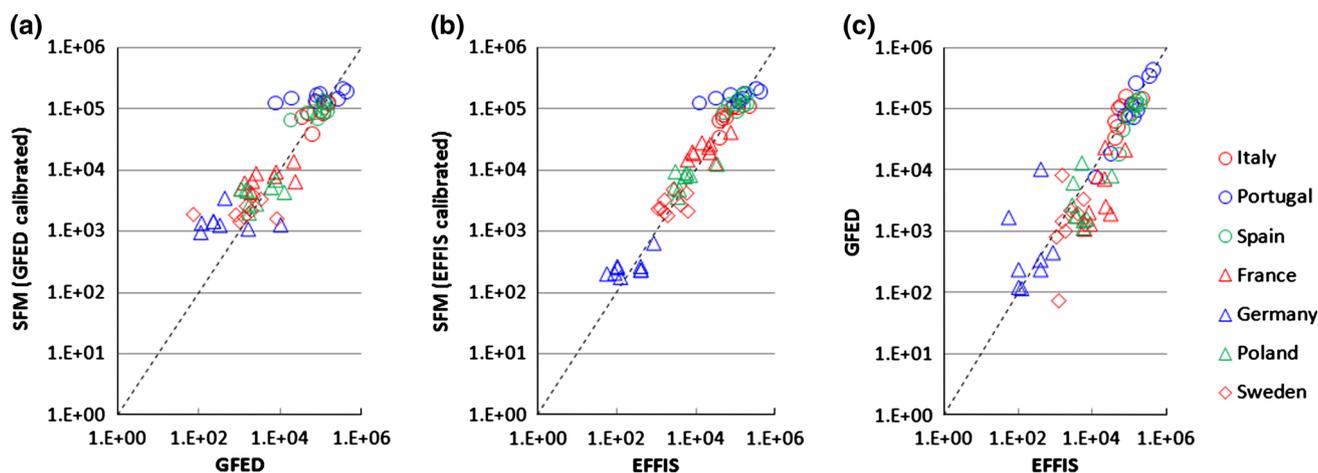
Table 1 reports performance of the SFM model (GFED and EFFIS calibrated) in terms of burned area for seven countries: Italy, Portugal, Spain, France, Germany, Poland, and Sweden. We have selected these countries because their data reported in EFFIS cover the entire period 2000–2008. An evaluation of GFED with EFFIS data is also reported for comparison. Based on the annual values for the historical period 2000–2008, we report mean absolute error (MAE) in thousands of hectares and

Table 1 SFM performance in terms of modelled annual burned areas for the historical period 2000–2008 for selected countries

Country	SFM versus GFED		SFM versus EFFIS		GFED versus EFFIS	
	r	MAE	r	MAE	r	MAE
Italy	0.664	26.90	0.677	29.20	0.644	34.70
Portugal	0.716	108.00	0.790	80.00	0.944	29.70
Spain	0.652	26.30	0.677	29.60	0.935	31.80
France	0.565	5.35	0.753	11.40	0.639	15.40
Germany	−0.106	2.11	0.848	0.14	0.163	1.36
Poland	0.398	2.45	0.703	4.61	0.341	6.04
Sweden	−0.006	1.49	0.256	1.51	0.004	2.08

GFED and EFFIS data were used for model calibration and consecutive benchmarking. r is the Pearson's correlation coefficient and MAE is the mean absolute error (in thousands of hectares)

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[2] The consultations were hosted by the Expert Group on Forest Fires (EGFF) of the European Commission http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetail&groupID=416.

Fig. 1 Scatter plots of yearly burned areas (SFM modelled versus reported, and GFED versus EFFIS) in hectares on a log scale for selected countries

Pearson's correlation coefficient r. Generally, the agreement of the SFM model with EFFIS data is comparable or even better than the agreement of GFED with EFFIS. However, SFM notably has problems reproducing historical data for Portugal (see Fig. 1). A closer look at annual burned areas in Portugal uncovers the inability of the model to catch considerable peaks in 2003 and 2005. This is an instance of the general difficulty which mechanistic fire models suffer in simulating burned area for years with severe fire seasons. This limitation is due to incomplete description of fuel and weather interactions as well as an inadequate representation of the suppression probability of multiple simultaneous fires (Thonicke et al. 2001; Migliavacca et al. 2013). The variability of modelling accuracy across the selected test countries should be taken into account for future interpretation.

Figure 1 reports the scatter plot of observed (EFFIS and GFED) and modelled annual burned area. Both Fig. 1 and Table 1 show that SFM provides better agreement with EFFIS data than with GFED data. This might be due to the fact that GFED products suffer from omission errors when fires are of relatively small size (Kaiser et al. 2012).

The results of the comparison tests we performed show reasonable model performance as compared to GFED dataset in reproducing EFFIS data for a set of selected countries at a yearly time scale. In contrast to the EFFIS data, GFED provides spatially and temporarily consistent coverage at the European scale and is freely available. Therefore, we used GFED for final EU-wide model calibration and projections even though the agreement of the model is better with EFFIS for the analysed subset of EU countries. For projections into future periods, we do not utilize burned areas at the annual temporal resolution and estimate only 10-year averages for larger regions.

Regional impacts of adaptation strategies

In this section, we apply the adaptation strategies described above in "Adaptation strategies" to three European regions: Mediterranean (France, Greece, Italy, Portugal, Spain), the Balkan region and Eastern European countries (Croatia, Montenegro, Serbia, Slovenia, Slovakia, Hungary, Bulgaria, Macedonia, Czech Republic, Romania), and Central EU and Baltic countries (Austria, Germany, Belgium, The Netherland, Poland, Latvia, Lithuania, Estonia). In the analysis, we use 2000–2008 as the reference period, and three future periods: 2026–2035, 2046–2055, and 2086–2095 for impact and adaptation assessments. We calculate average annual burned areas over these future 10-year time intervals and report the results as average values for 2030, 2050, and 2090, respectively, while the average value for 2000 was calculated based on the historical period 2000–2008. The GFED-calibrated SFM model with climate projections coming from MRI-CGCM2.3.2, CNRM-CM3, and CSIRO-Mk3.0 GCMs is further referred to as SFM$_{MRI}$, SFM$_{CNRM}$, and SFM$_{CSIRO}$, respectively.

Projected impacts and the effect of fuel removal (prescribed burnings) as assessed by the SFM model for European regions are presented in Fig. 2. SFM$_{CNRM}$ and SFM$_{MRI}$ deliver the greatest and the smallest impacts, respectively, for all three aggregated European regions, while the impact projection of SFM$_{CSIRO}$ falls between these estimations.

For the Mediterranean region (Fig. 2a), the yearly average burned area is projected to increase by approximately 150–220 % in 2090 relative to 2000. This result is in agreement with predictions of a 140 % increase in burned areas for the time period 2070–2100 relative to 1985–2004, a figure obtained independently for the SRES
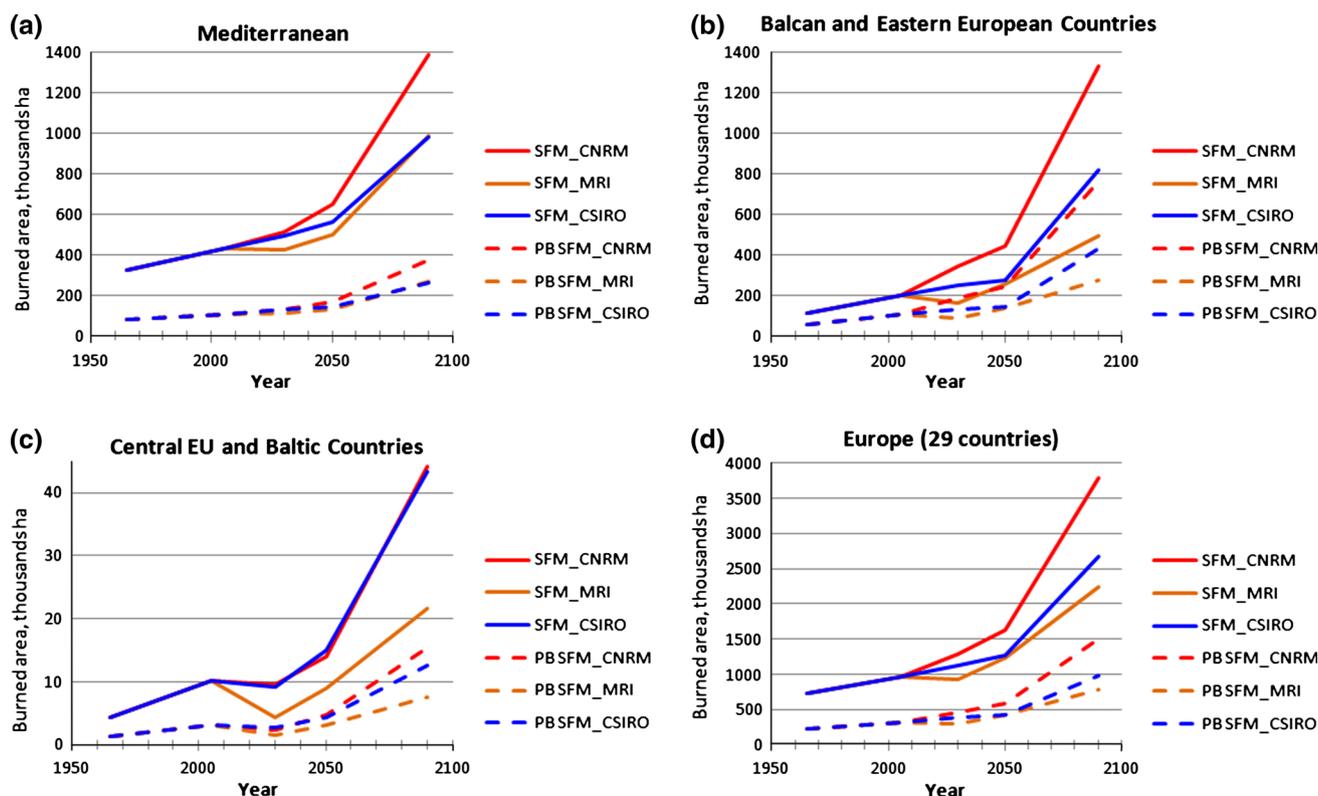
Fig. 2 Projected impacts and effect of fuel removal (prescribed burnings) on burned areas (in thousands of hectares) as assessed by SFM$_{MRI}$, SFM$_{CNRM}$, and SFM$_{CSIRO}$ models (all calibrated using GFED) for European regions. *Solid lines* represent "no adaptation" scenario, *dashed lines* prescribed burnings (PB)

A2 scenario using a different (statistical) modelling approach (Amatulli et al. 2013). Relative to this baseline, prescribed burnings are projected to decrease the yearly burned areas on average by 74 % in the Mediterranean by 2090. In the "no adaptation" scenario, the model predicts that the Balkan and Eastern European countries (Fig. 2b) will suffer an extreme 150–560 % increase in burned areas in 2090 relative to 2000. In this region, prescribed burnings can potentially decrease the average yearly burned area in 2090 by about 47–69 %. Results for Central EU and Baltic countries are shown in Fig. 2c, indicating an increase in burned areas by approximately 120–340 % in 2090 over 2000. As in the other regions, the projected decrease in annual average burned areas due to prescribed burnings is about 70 %. In Fig. 2d, we show the results aggregated for the entire European region including 29 countries (all the regions analysed above in Fig. 2a–c plus six additional countries: Switzerland, Finland, Sweden, Turkey, Norway, and UK. The projected impact of prescribed burnings in the entire European region does not substantially change over the considered future time slices (2030, 2050, 2090) and, in 2090, promises a 65–67 % reduction in burned area relative to the "do nothing" scenario.

Our results draw out significant potential consequences of the SRES A2 climate change scenario in Europe.

Studies on North America produce a similarly large impact assessment under SRES A2: burned areas in Alaska and western Canada are projected to increase by 250–450 % by the last decade of the twenty-first century as compared to 1991–2000 (Balshi et al. 2009). The results of our study in terms of the estimated impact of prescribed burnings on burned areas, even though not always directly comparable, are in line with other studies on the effectiveness of prescribed burning for fire hazard reduction. For instance, a difference of about three times between the average size of a wildfire in treated and untreated areas in US has been shown (Fernandes and Botelho 2003). Similar results have also been obtained in Australia, where the average wildfire size was reported to be 50 % smaller in treated areas.

For illustration purposes, we present the maps depicting the impact of prescribed burnings (fuel removal) in 2090s (Fig. 3). For this analysis, we apply spatially explicit (pixel level) calibration of q mentioned in the "Modelling strategy" The SFM$_{MRI}$ model (GFED-calibrated on the historical period 2000–2008) estimates the average burned area in 2090s under the "no adaptation" and the "prescribed burnings" scenarios. The maps demonstrate that prescribed burnings may considerably decrease burned area in the European region in the future with the most
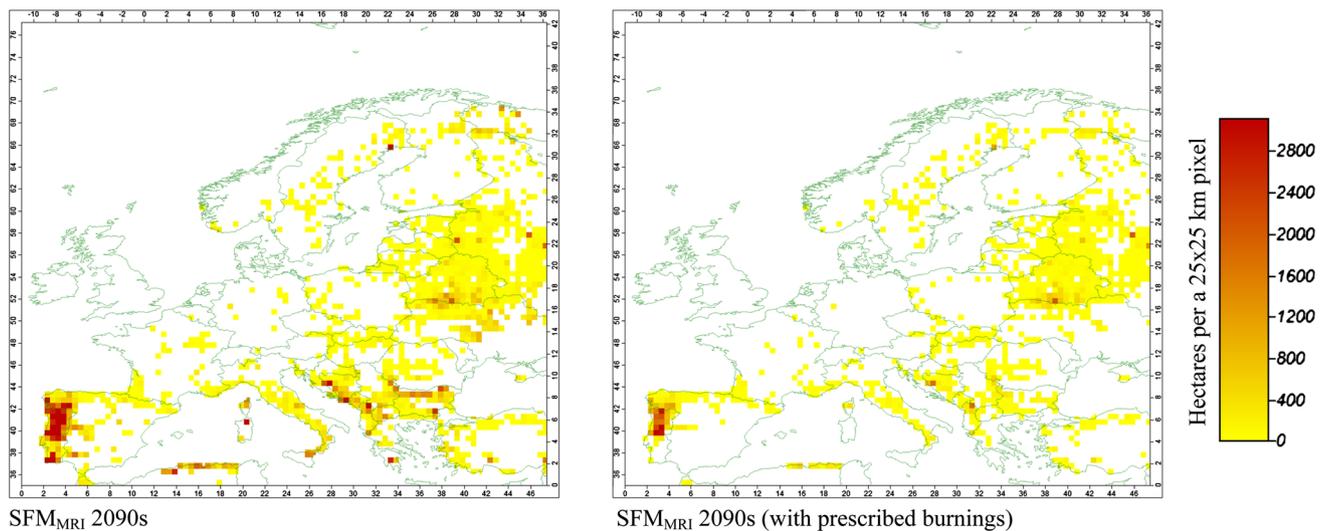
Fig. 3 Spatially, explicit projection of yearly burned areas (hectares per a 25 × 25 km pixel) estimated by SFM$_{MRI}$ model in 2090s with and without prescribed burnings

prominent reduction visible in the Mediterranean as well as the Balkan and Eastern European regions.

We further analysed how changes in suppression strategies, described in terms of the parameter q, impacts the accumulated burned areas. We performed a sensitivity analysis on q by varying this proxy to represent changes in each country's overall fire suppression abilities. A country-specific burned area corresponding to a calibrated q value is taken as unit value, and changes in burned areas with respect to ±10 % changes in q are presented in Fig. 4 for the SFM model, calibrated using GFED data for years 2000–2008 for eight selected countries. In general, a relative change in q of ±10 % leads to a relative change in burned areas of ±30 %. The magnitude of this change depends nonlinearly on the initial value of q, with wider ranges observed for bigger values of q. An increase in q can be interpreted as an improvement in active response to forest fires in a region and leads to a decrease in the burned area (Fig. 4).

In our modelling framework, fire suppression is not limited to a particular technique and potentially might include the use of fire itself, e.g. backfire, burning out, and counter firing (Silva et al. 2010). Even though preventive measures (fuel removal) were handled explicitly, the improved suppression was described only through a proxy variable aggregating detection, resource availability, and management. The existing modelling framework does not allow for separation of those different factors. Conclusions regarding the relative efficacy of investment in proactive and reactive measures cannot be rigorously undertaken in this framework for two reasons: first, due to the general nature of q in contrast to specific definition of prescribed burnings; and second, because of the missing cost
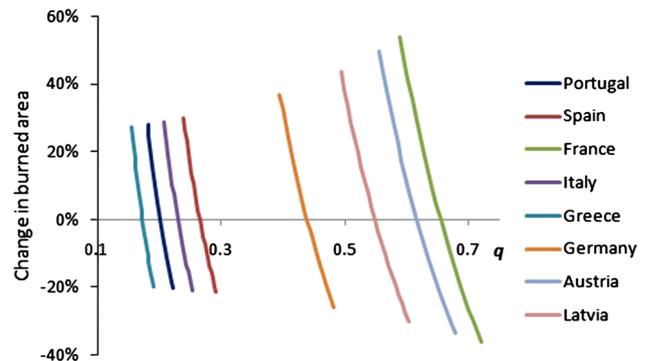
Fig. 4 Sensitivity analysis of suppression efficiency for the SFM model calibrated using GFED data for years 2000–2008. Changes in burned areas per country are in percents relative to burned area corresponding to calibrated value of q (values of q vary within ±10 % range)

component. Nevertheless, the presented framework allows for the assessment of a combined application of both modelled adaptation options because the model parameters relevant to prescribed burnings (fuel removal) and improved suppression are separable from each other, i.e. their respective burned area reduction factors multiply in the case of a combined application.

Conclusions

In this paper, we presented a framework for assessing the potential effectiveness of two adaptation options: (1) prevention through fuel reduction via prescribed burnings and (2) active response through better fire suppression. With

the help of SFM, we carried out a model-based quantification of the potential effectiveness of prescribed burnings with respect to anticipated climate change under SRES A2 scenario on a pan-European scale.

The two options that we explored were discussed and selected in consultation with stakeholders, because, first, at a higher level of abstraction they represent two classes of approaches—prevention and reaction—and at the same time allow meaningful quantification and interpretation. Second, these options are potentially applicable at pan-European scale and, third, can be handled within the state-of-the-art large-scale fire models. Other relevant options, such as increasing land fragmentation and species conversion, cannot be properly modelled within the selected framework, because, first, the fire spread is estimated without taking into account the fragmentation of landscape, and second, because of a simplified representation of the fuel.

The simplified approach for modelling future daily weather that we have used for this study has several limitations, including the same number of "wet" days per month as in the historical period, and unchanged values for wind speed and relative humidity. Using a full set of future daily weather, variables generated by a "reliable" climate model would imply processing a much larger amount of data, but is definitely a way to go in the future to refine projections.

The quantitative results we obtained for model benchmarking on a historical period for selected countries show reasonable performance of the SFM model in terms of agreement of the modelled burned areas in Europe with observed data provided by EFFIS. However, the modelling accuracy still needs to be improved and the highlighted issues point to the directions for further development. As there are discrepancies between GFED and EFFIS data, the projections we obtained using GFED as a calibration dataset should be treated with caution. Our projections of climate change impact (without adaptation) and assessments of prescribed burnings efficiency (under present climate) are both derived as by-products for comparison purposes, and are in line with existing literature. However, there are no other studies providing quantitative estimates for direct comparison with our projections except for climate impact assessment on forest fires under SRES A2 scenario for Mediterranean countries (Amatulli et al. 2013). Our estimation of potential increase in annual burned areas in Europe under SRES A2 and "no adaptation" scenario is about 200 % by 2090, compared with 2000–2008. The application of prescribed burnings has a potential of keeping that increase below 50 %. Improvements in fire suppression might reduce this impact even further; e.g. boosting the probability of putting out a fire within a day by 10 % country wide would result in about 30 % decrease in annual burned area for that particular country. Since we did not include all potentially available adaptation options into our analysis, the effects of climate change can potentially be reduced beyond these indicative levels. Future efforts should be oriented at exploration of relevant costs and benefits that would ultimately define the feasible level of the impact reduction.

The need to overcome the current modelling limitations identified in the course of this research calls for a fundamental upgrade of the existing continental-scale fire models. This major step, however, is beyond the scope of the presented research and therefore is left for future elaborations.

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