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# Air quality impacts of European wildfire emissions in a changing climate

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**Abstract.** Wildfires are not only a threat to human property and a vital element of many ecosystems, but also an important source of air pollution. In this study, we first review the available evidence for a past or possible future climate-driven increase in wildfire emissions in Europe. We then introduce an ensemble of model simulations with a coupled wildfire–dynamic-ecosystem model, which we combine with published spatial maps of both wildfire and anthropogenic emissions of several major air pollutants to arrive at air pollutant emission projections for several time slices during the 21st century. The results indicate moderate wildfire-driven emission increases until 2050, but there is a possibility of large increases until the last decades of this century at high levels of climate change. We identify southern and north-eastern Europe as potential areas where wildfires may surpass anthropogenic pollution sources during the summer months. Under a scenario of high levels of climate change (Representative Concentration Pathway, RCP, 8.5), emissions from wildfires in central and northern Portugal and possibly southern Italy and along the west coast of the Balkan peninsula are projected to reach levels that could affect annual mean particulate matter concentrations enough to be relevant for meeting WHO air quality targets.

## 1 Introduction

Here we will first summarise the importance of wildfires on air quality in Europe (Sect. 1.1), then review what is known about the influence of past climate change on European wildfires (Sect. 1.2) and existing efforts to model change in future wildfire emissions (Sect. 1.3). Based on the findings described in the introduction, we combine inventories, scenarios and model-based future projections of anthropogenic and wildfire emissions with climate, terrestrial-ecosystem and fire model simulations (see Methods). This will identify potential geographical hotspots where certain pollutants from wildfires might reach or exceed anthropogenic emission levels, or become relevant for air quality targets as a first indication of where potential health-related risks may be caused by increased wildfire activity as a result of climate change.

### 1.1 Wildfire impact on air quality and the role of climate change

Air quality is strongly influenced by local to global emissions of airborne pollutants, atmospheric chemistry, removal mechanisms, as well as atmospheric transport (Seinfeld and Pandis, 2012). While most pollutants of anthropogenic origin are subject to increasingly strict legislation, which has avoided further deterioration of air quality with economic growth and led to an overall significant decrease in emissions in Europe and improvement of European air quality

(Cofala et al., 2007; Monks et al., 2009; Amann et al., 2011; Klimont et al., 2013; European Commission National Emissions Ceiling directive: http://ec.europa.eu/environment/air/pollutants/ceilings.htm), wildfires, which emit large amounts of aerosols and chemically reactive gases (Langmann et al., 2009), are predicted to increase with climate change (Scholze et al., 2006; Krawchuk et al., 2009; Pechony and Shindell, 2010; Moritz et al., 2012; Kloster et al., 2012; Knorr et al., 2016a).

Meteorological fire indices are routinely used to assess the likelihood of fire occurrence and they generally predict an increased fire risk with warmer and drier weather (van Wagner and Forest, 1987). This is consistent with evidence from charcoal records, which have revealed a higher fire activity associated with a warmer climate (Marlon et al., 2008). A large increase in the forest area burned annually in the United States in recent decades (Liu et al., 2013) has also been associated with warming and drying trends, at least for the southwestern part of the country (Westerling et al., 2006). For Europe, some recent publications based on climate model output combined with fire danger indices have predicted large increases in fire activity in Europe (Amatulli et al., 2013; Bedia et al., 2014). This has important consequences for air quality management, because wildfires are mostly outside the reach of policy measures as they are influenced by humans in complex and often unpredictable ways (Bowman et al., 2011; Guyette et al., 2002; Mollicone et al., 2006; Archibald et al., 2008; Syphard et al., 2009). Large fires, once started, often escape human control altogether (Chandler et al., 1983) and more significantly, human control through fire suppression may increase fire risk in the long term (Fellows and Goulden, 2008), resulting in less frequent but more severe wildfires.

The most abundant pollutants emitted by fires in extratropical forests, which includes typical wildland fires in the Mediterranean, are carbon monoxide (CO), particulate matter (aerosols, including organic carbon and soot), methane ($CH_4$) and various non-methane hydrocarbons and volatile organic compounds (Akagi et al., 2011). Not all of these species are explicitly included in large-scale emission inventories, for example organic carbon, which is a major part of total primary particulate matter emitted by fires. However, it appears that in general, total wildfire emissions of most components aggregated for Europe are 1 to 2 orders of magnitude lower than those from anthropogenic sources (Granier et al., 2011). During large fire events, however, forest fires in Europe can have a major impact on air quality (Miranda et al., 2008; Konovalov et al., 2011).

### 1.2 Impact of past climate change on European wildfire emissions

Since the beginning of the 20th century, climate in Europe has been warming by 0.1 °C per decade, a trend that is significant at the 95 % level. At the same time, there has been a significant increase of annual precipitation by around 0.9 mm per decade in northern Europe, and a decline of between 0.3 and 0.5 mm per decade for southern Europe and the Mediterranean Basin, where the higher estimate is also significant (Harris et al., 2014). However, before addressing the question of whether past climate change has had an impact on wildfire emissions in Europe, it is useful to consider how these emissions are described in simulation models. Mathematically, emissions from wildfires are routinely calculated as the product of area burned, fuel load, the combustion completeness of the fuel and the emission factor, which translates combusted biomass into emissions of a particular species or group of aerosols. Little is known about whether climate change has affected emission factors or combustion completeness. Fuel load can be expected to change with vegetation productivity, which is influenced by climate and atmospheric $CO_2$, as well as by landscape management. While again little is known about the impact of changing landscape management, dynamic vegetation models can in principle be used to address the impact of climate and $CO_2$. The remaining factor is the change in burned area and the attribution of changing burned area to climate change as the main possibility of attributing changes in emissions to climate change.

The most prominent example of a regional increase in wildfire activity and severity that has been attributed to recent climate change is found in the western United States (Westerling et al., 2006), where progressively earlier snowmelt in response to warming has led to forests drying up earlier in the year, thus making them more flammable. The western US is a region characterized by exceptionally low atmospheric humidity during the summer, as well as by low human population density. A very close correlation was observed between climate factors and fire frequency, which showed a clear upward trend since the 1970s.

The situation for other regions including Europe, however, is more ambiguous. Fire emissions from boreal forests, where human population density can be as low as in the western US, represent only a small part of European wildfire emissions (van der Werf et al., 2010), and Finland and Sweden in particular have very low wildfire emissions (JRC, 2013). The Mediterranean and southern European regions, on the other hand, where most wildfires in Europe occur (San Miguel and Camia, 2010), are characterized by much more intense human land management going back thousands of years. The period since the 1970s, in particular, was one in which large tracts of land, previously managed intensively for grazing and browsing, were abandoned. A study by Koutsias et al. (2013) shows an upward trend in burned area for Greece from about 1970, similar to the one found for the western US and a significant correlation between burned area and climatic factors, even though their study did not analyse the role of any socio-economic drivers as possible causes. However, Pausas and Fernández-Muñoz (2012) in a study of eastern Spain attributed a very similar temporal trend in fire frequency to an increasing lack of fuel control as a result of massive land flight. Along the same lines, Moreira et al. (2011) found that during recent decades, changes in land use have generally increased flammability in southern Europe, mainly due to land abandonment and associated fuel build-up and the spread of more flammable land cover types such as shrublands. In fact, a closer inspection of the data series by Koutsias et al. reveals that most of the increase happened during the 1970s, indicating land abandonment as a possible cause.

High-quality quantitative data on Europe-wide fire occurrence, recompiled in the European Forest Fire Information System (EFFIS), are only available starting from the 1980s. This is unfortunately just after the previously described drastic increase in fire occurrence for various regions over the Mediterranean basis. Data by EFFIS show a general decreasing trend in burnt area (1985–2011) over the European part of the Mediterranean Basin (Spain, France, Italy and Greece), except Portugal where no trend was observed (Turco et al., 2016). However, just as for Greece and a region in Spain, data for Italy show an upward trend during the 1970s. It is hypothesised that the decreasing trend in burned area over the last decades is due to an increased effort in fire management and prevention after the big fires of the 1970s and 1980s (Turco et al., 2016). Of the other EU countries, only Croatia has levels of burned area per year comparable to the southern European countries already referred to (i.e. above 20 000 ha year$^{-1}$ on average), but shows no trend. Bulgaria shows extremely large year-to-year fluctuations in burned area, but no discernable trend. No large-scale data are available for the European part of Russia (JRC, 2013). There is therefore no evidence that burned area from wildfires has increased in Europe over the past decades and by implication no evidence a climate-driven increase in pollutant emissions from wildfires.

### 1.3 Predicting changes in wildfires emissions

As for past changes, any predictions of future changes in pollutant emissions from wildfires suffer from the fact that little is known about the determinants of several of the factors used to compute emission rates: burned area, fuel load, combustion completeness and emission factors (Knorr et al., 2012). In particular, no study has so far considered changes in emission factors and even complex global fire models only use a fixed set of values for combustion completeness depending on the type of biomass combusted (Kloster et al., 2012; Migliavacca et al., 2013). At most, model-based predictions of fire emissions are based on simulated changes in burned area and fuel load alone, assuming no change in either emission factors or combustion completeness as a result of changes in climate, management or ecosystem function. Because there are no large-scale direct observations of fuel load, values of fuel simulated by models carry a large margin of uncertainty (Knorr et al., 2012; Lasslop and Kloster, 2015).

Most of the early predictions of future fire activity did not simulate burned area, with the exception of Scholze et al. (2006), who however only report probability of change. For example, the pioneering global studies by Krawchuk et al. (2009) and Pechony and Shindell (2010) essentially predict number of fires – which the authors call "fire activity". Number of fires, however, is not a suitable indicator of fire emissions, unless one would assume not only constant emission factors and combustion completeness, but also no change in fuel load and an average size of fire. Fuel load, however, has been shown to change substantially with climate and $CO_2$ fertilisation (Kloster et al., 2012; Martin Calvo and Prentice, 2015; Lasslop and Kloster, 2015) and to have a major impact on predicted changes in total fire-related carbon emissions (Knorr et al., 2016a). It has also been observed that average fire size changes substantially with human population density (Archibald et al., 2010; Hantson et al., 2015).

While Pechony and Shindell (2010) still concluded that temperature would become the dominant control on fire activity during the 21st century, Moritz et al. (2012) found that precipitation and plant productivity will also play key roles. Using an empirical model based on plant productivity and a range of climate drivers and predicting the number of fires, they found a mixed picture, but no universal increasing trend towards more fires, with large parts of the tropics and subtropics likely seeing a decrease in fire activity, rather than an universal increasing trend towards more fires.

Contrary to the statistical approaches by Archibald et al. (2010), Knorr et al. (2014) and Bistinas et al. (2014), who also found that increasing human population leads to less burned area, Pechony and Shindell (2010) use an approach first developed by Venevsky et al. (2002), where the number of fires is modelled in proportion to the number of ignitions, most of them human. Human ignitions are assumed to increase proportionally with human population until some threshold, where fire suppression leads to a downward modification. More comprehensive fire models predict not only number of fires, but also fire spread and thus burned area. In fact, most of the existing global fire models to-date that are able to predict burned area use the approach by Venevsky et al. (2002), where burned area is considered at the end of a chain of predictions that starts from the number of ignitions. This applies to the global models of Arora and Boer (2005), Thonicke et al. (2010), Kloster et al. (2010) and Prentice et al. (2011).

This inherent view that burned area is driven mainly by the number of ignitions has recently been criticised by Knorr et al. (2014) who, using several independent satellite-observed burned-area data sets, developed a semi-empirical model of fire frequency based on climatic indices and human population density alone. Based on statistical analysis, the study came to the conclusion that human presence overwhelmingly leads to a decrease in burned area, even for areas with very low population density, such as in large parts of the Australian continent. The same view is supported by a review of the impacts of land management on fire hazard by Moreira et al. (2011), showing that at least in southern Europe, land use changes associated with fewer people almost always lead to increased fire risk and vice versa. Other statistical studies by Lehsten et al. (2010) for Africa and by Bistinas et al. (2013, 2014) for the globe also found a predominantly negative impact of population density on burned area, supporting the view that most fire regimes on the globe are not ignition limited but rather ignition saturated (Guyette et al., 2002; Bowman et al., 2011). Since the view of ignition saturation is in direct contrast to the implicit assumption of burned area increasing with number of ignitions – all else being equal – that is included in most large-scale fire models, it must be concluded that there is so far no consensus on the mechanisms that drive changes in fire frequency, be they climatic, socio-economic or a combination of both.

At the regional scale, a few studies have attempted to predict future changes in fire regime, most of them by predicting changes in fire weather: e.g. Stocks et al. (1998), Flannigan et al. (2005), and for Europe, Moriondo et al. (2006) and Bedia et al. (2014). One study, Amatulli et al. (2013), goes beyond those by developing a statistical model of burned area based on a selection of indicators that form part of the Canadian Fire Weather Index (van Wagner and Forest, 1987). One problem faced by the latter study is that the future climate regime simulated by climate models is often outside the training regime used to develop the statistical model, leading to uncertain results.

An overview of relevant model results for Europe is offered in Table 1. The study by Amatulli et al. (2013) previously referred to is also the one that predicts the most extreme changes in burned area in the Mediterranean (Table 1). This might be attributable to a lack of representation of vegetation effects on fire spread or burned area: when precipitation decreases while meteorological fire risk increases, fire spread is increasingly impeded by lower and lower fuel continuity (Spessa et al., 2005). However, as much as this study appears to be an outlier, all predict an increase in either carbon emission or burned area in Europe towards the later part of the 21st century, mostly in southern and eastern Europe. There is, however, no consensus on the underlying mechanism of the increase. For instance, while Migliavacca et al. (2013) predict a rate of increase for emissions greater than the rate of increase for burned area – i.e. more fuel combusted per area – Knorr et al. (2016a) predict the opposite, but with a climate effect on burned area that still overrides the effect of decreasing fuel load. In the same line, Wu et al. (2015) predict a population-driven increase for eastern Europe using SIMFIRE (SIMple FIRE model), but mainly a climate-driven increase when using SPITFIRE (SPread and InTensity of FIRE), more similar to the results by Kloster et al. (2012) and Migliavacca et al. (2013).

## 2 Methods

### 2.1 Simulations

None of the published simulation studies of future European fire emissions consider emissions at the level of chemical species or amounts of specific aerosols, hence do not provide indications on the significance for air quality. Therefore, we have taken existing simulations by Knorr et al. (2016a) that predict emissions in combusted carbon amounts (Knorr et al., 2012) based on changing climate, atmospheric $CO_2$ and human population density, considering changing vegetation type and fuel load. The effect of changing land use is considered implicitly by the use of population density (Knorr et al., 2016b). We use temporal changes predicted by these simulations to rescale observation-based emission estimates in order to arrive at more realistic spatial patterns that would not be possible using coupled climate–wildfire simulations alone. A comparison of LPJ-GUESS-SIMFIRE (Lund–Potsdam–Jena General Ecosystem Generator-SIMple FIRE model) burned area for Europe and observations is shown in Wu et al. (2015). Agreement was within 20–50 % in most parts of Europe, including the Mediterranean, which is the largest fire-prone region on the continent.

Simulations of wildfire carbon emissions are based on an ensemble of eight climate model simulations from the Climate Model Intercomparison Project 5 (Taylor et al., 2012). For each climate model, two runs are used, each one driven by greenhouse gas emissions from either RCP4.5 (medium climate stabilisation case) or 8.5 (baseline case for greenhouse gas emission, van Vuuren et al., 2011).

Two further simulations were performed where the standard parameterisation of SIMFIRE has been changed to one derived from optimisation against MCD45 global burned area (Roy et al., 2008). This was done only with one climate model (MPI-ESM-LR, see Knorr et al., 2016a), in order to test the sensitivity of the SIMFIRE simulations against changes in its parameterisation, which normally is derived by optimisation against GFED3.1 burned area (van der Werf et al., 2010).

### 2.2 Model input data

Gridded fields of monthly simulated precipitation, diurnal mean and range of temperature and solar radiation are bias-corrected against mean observations (Harris et al., 2014) for 1961–1990 and together with global mean observed and future-scenario $CO_2$ concentrations (Meinshausen et al., 2011) used to drive simulations of the LPJ-GUESS global dynamic vegetation model (Smith et al., 2001) coupled to the SIMFIRE fire model (Knorr et al., 2012, 2014). Plant mortality during fire and the fraction of living and dead biomass consumed by the fire are all assumed to be fixed across time (see Knorr et al., 2012). The simulations are carried out on an equal-area grid with a spacing of 1° in latitudinal direc-

**Table 1.** Overview of climate change modelling results for wildfires that cover Europe.

| Reference | Output | Domain | Method | Input | Result for Europe |
|---|---|---|---|---|---|
| Scholze et al. (2006) | burned area | Globe | LPJ-GlobFirM<br>vegetation, empirical fire model<br>no human impact | 16 GCMs, 52 GCM-scenario combinations | Significant decrease in north-eastern Europe, increase in western Europe, Italy and Greece, mixed results for Spain |
| Kloster et al. (2012) | carbon emissions | Globe | CLM<br>process based model | MPI and CCM GCMs,<br>SRES A1B,<br>factorial experiments | +116 % (MPI) or +103 % (CCM) between 1985–2009 and 2075–2099; increase mostly in south-central and eastern Europe, decrease in Mediterranean |
| Migliavacca et al. (2013) | carbon emissions | Europe, parts of Turkey and northern Africa | CLM<br>adapted for Europe | 5 RCMs | from 1960–1990 to 2070–2100 +63 % for Iberia and +87 % for rest of southern Europe; increase in fuel load |
| Amatulli et al. (2013) | burned area | Portugal, Spain, French Mediterranean, Italy, Greece | CFWI combined with several statistical models,<br>different CFWI codes and statistical models by country | Single RCM, SRES A2,<br>B2 | Between 1985–2004 and 2071–2100 +60 % for Europe and +500 % for Spain (B2) or +140 % for Europe and +860 % for Spain |
| Bedia et al. (2014) | SSR of CFWI | Southern Europe, northern Africa | CFWI<br>meteorology only | 6 GCM-RCM combinations<br>SRES A1B | Significant increase from 1971–2000 to 2041–2070 for Portugal, Spain, Italy, Greece and Turkey, to 2071–2100 the same plus French Mediterranean and Balkans |
| Wu et al. (2015) | burned area | Europe | LPJ-GUESS-SIMFIRE,<br>LPJ-SPITFIRE<br>process-based vegetation and fire models | 4 GCMs, RCP2.6 and 8.5 scenarios | +88 % (SIMFIRE) or +285 % (SPITFIRE) from 1971–2000 to 2071–2100 for RCP8.5, especially in eastern Europe due to population decline (SIMFIRE) or climate (SPITFIRE) |
| Knorr et al. (2016a) | carbon emissions | Globe | LPJ-GUESS-SIMFIRE<br>process-based vegetation,<br>semi-empirical fire model | 8 GCMs, RCP4.5 and 8.5 scenarios | During 21st century large increase due to Population decline combined with increased burned area driven by climate warming, while fuel load is decreasing; significant increases in central, eastern, southern Europe |

CFWI: Canadian Fire Weather Index; CLM: Community Land Model; GCM: General Circulation Model; RCM: Regional Climate Model; SRES: Special Report on Emissions Scenarios; RCP: Representative Concentration Pathway; SSR: Seasonal Severity Rating.

tion and 1° in longitudinal direction at the equator, increasing in degrees longitudinally towards the poles (with approximately constant 110 km by 110 km grid spacing). For a detailed description of bias correction and spatial interpolation see Ahlström et al. (2012) and Knorr et al. (2016a).

Population density until 2005 is taken from gridded HYDE data (History Database of the Global Environment, Klein-Goldewijk et al., 2010). Future population scenarios are from the Shared Socio-economic Pathways (SSPs; Jiang, 2014), using SSP5 (a conventional development scenario assuming high population growth and fast urbanisation for Europe or slight population decline in some eastern European countries, differing from most of the rest of the world with low population growth and fast urbanisation for developing regions), SSP2 (middle of the road scenario, with medium population growth and urbanisation for Europe and the rest of the world) and SSP3 (a fragmented world assuming low population growth or strong population decline, combined with slow urbanisation for Europe, compared to high population growth and slow urbanisation for developing regions). Gridded population distributions beyond 2005 are produced by separate rescaling of the urban and rural populations from HYDE of 2005 (see Knorr et al., 2016a for details).

### 2.3 Data for current wildfire and anthropogenic emissions

In order to simulate realistic scenarios of the spatial patterns of wildfire emissions in Europe, we use emission data from the Global Fire Emissions Database Version 4.1 (GFED4.1s), based on an updated version of van der Werf et al. (2010) with burned area from Giglio et al. (2013) boosted by small fire burned area (Randerson et al., 2012). We use the mean annual course of monthly emissions at a resolution of 0.5° by 0.5° from the sum of boreal and temperate forest fires during the years 1997 to 2014 as a climatology of present wildfire emissions for black carbon (BC), CO, $NO_x$, particulate matter up to 2.5 microns ($PM_{2.5}$) and $SO_2$. In order to avoid the inclusion of agricultural burning erroneously classified as wildfires as much as possible, we only use the months May to October from the climatology.

For anthropogenic emissions of air pollutants, we use the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2011) estimates developed within the ECLIPSE project (Evaluating the Climate and Air Quality Impacts of Short-lived Pollutants, Stohl et al., 2015). Specifically, we use the GAINS version 4a global emissions fields (Klimont et al., 2013; Stohl et al., 2015; Granier et al., 2011), which are obtained for 2010 (base year), 2030 and 2050 at 0.5° by 0.5° resolution from the ECCAD (Emissions of atmospheric Compounds and Compilation of Ancillary Data) database. The future emissions for 2030 and 2050 are available for two scenarios (Table 2): current legislation (CLE), which assumes efficient implementation of existing air pollution laws and the maximum technically feasible reduction (MFR), where all technical air pollution control measures defined in the GAINS model are introduced irrespective of their cost. We do not use PEGASOS (Pan-

**Table 2.** Total anthropogenic emissions for European study area.

| Data set | Description | Species | 2010 | 2030 | 2050 | 2090 |
|---|---|---|---|---|---|---|
| ECLIPSE<br>CLE | Current legislation | CO | 37 689 | 30 183 | 22 720 | *16 970* |
| | | $PM_{2.5}$ | 2712 | 2370 | 2031 | *1581* |
| | | BC | 465 | 399 | 224 | *165* |
| | | $NO_x$ | 9581 | 7929 | 4207 | *3130* |
| | | $SO_2$ | 10 680 | 7380 | 3697 | *2815* |
| PEGASOS<br>BL-CLE | Baseline CLE, no change in emission factors after 2030 | CO | 32 011 | 18 870 | 17 573 | 8479 |
| | | BC | 525 | 153 | 99 | 29 |
| | | $NO_x$ | 8253 | 3775 | 2936 | 2596 |
| | | $SO_2$ | 10 533 | 3419 | 3150 | 2837 |
| ECLIPSE<br>MFR | Maximum feasible reduction | CO | | 11 538 | 11 732 | *5866* |
| | | $PM_{2.5}$ | | 567 | 552 | *276* |
| | | BC | | 55 | 50 | *33* |
| | | $NO_x$ | | 1519 | 1478 | *1020* |
| | | $SO_2$ | | 1560 | 1443 | *1042* |
| PEGASOS<br>MFR-KZN | MFR with GDP-driven decline in emission factors towards 2100 | CO | 30 575 | 12 587 | 10 824 | 4977 |
| | | BC | 521 | 125 | 64 | 27 |
| | | $NO_x$ | 7848 | 1881 | 1382 | 1291 |
| | | $SO_2$ | 10 160 | 1824 | 1291 | 900 |
| PEGASOS<br>450-MFR-KZN | MFR-KZN with 450 ppm atmospheric $CO_2$ stabilisation target | CO | 30 575 | 11 653 | 9074 | 4735 |
| | | BC | 521 | 101 | 42 | 23 |
| | | $NO_x$ | 7848 | 1585 | 1074 | 889 |
| | | $SO_2$ | 10 160 | 1298 | 680 | 395 |

Emissions in Tg $yr^{-1}$; GDP: gross domestic product. Number in italics: extrapolation by the authors.

European Gas-AeroSOls Climate Interaction Study) PBL (Netherlands Environmental Assessment Agency) emissions (Braspenning-Radu et al., 2016) because they do not include particulate matter, but instead we compare them to the emission scenarios used here (Table 1). In order to obtain a scenario with some further declining emissions, we extend the ECLIPSE GAINS CLE anthropogenic emissions data set to 2090 by scaling emissions in 2050 by the relative change of the population in each grid cell between 2050 and 2090 according to the SSP3 population scenario (low population growth and slow urbanisation for Europe). For MFR, we assume that emissions for all species in 2090 are half of what they are for 2050. A comparison of the extended ECLIPSE anthropogenic emission trends after 2050 can be made using the independent set of emission scenarios provided by the PEGASOS PBL emissions data set (Braspenning-Radu et al., 2016). Since this data set does not provide $PM_{2.5}$ emissions, the comparison is limited to CO, BC, $NO_x$ and $SO^2$. For CO and BC, the PEGASOS PBL CLE data show a stronger decline by than our extended ECLIPSE emissions, but for $NO_x$ and $SO_2$, the changes from 2050 to 2090 are very similar. For MFR, PEGASOS MFR-KZN has about the same total emission as those used here by 2090 (Table 2).

## 2.4 Method of analysis

We calculate future emissions by averaging simulated annual emissions for the same chemical species by European country using the Gridded Population of the World Version 3 country grid. We restrict the area of analysis to Europe west of 40° E. Only those countries resolved on the 1° equal area grid are included. Two groups of countries are treated as a single unit, namely Belgium, Netherlands and Luxembourg as "Benelux", and the countries of former Yugoslavia plus Albania as "Yugoslavia & Albania". One country – Moldova – was excluded because none the ensemble runs simulated any fire occurrence for present-day conditions. The observed climatology of emissions is then scaled at each grid cell according to which country it is located in. The scaling factor equals the mean annual simulated biomass emission of this country during the future period divided by the mean annual biomass emissions from 1997 to 2014 inclusive.

In the following, we compare anthropogenic and wildfire emissions of BC (black carbon), CO, $NO_x$, $PM_{2.5}$ (particulate matter up to 2.5 µm diameter) and $SO_2$, both on an annual average basis, and for the peak month of the fire season, i.e. during the month with highest wildfire emissions on average at the corresponding grid cell. We approximate monthly emissions at the peak of the fire season as one twelfth of annual anthropogenic emissions without emissions from the category "residential and commercial combustion", which is dominated by room heating in households and small commercial units and excludes combustion in industrial installation or power plants. Subtraction of the latter sector focuses on the relative contribution of emissions in the summer.

## 3 Results and discussion

### 3.1 Current observed patterns of air pollution against population density

By and large, we expect anthropogenic emissions to be spatially associated with areas of high population density and it is therefore interesting to consider how the two quantities are related. For emissions from wildfires one would expect a different relationship, as large wildfires are often associated with remote and sparsely populated areas, such as the boreal zone. As Fig. 1 shows, current anthropogenic emissions of CO, $PM_{2.5}$ and BC are generally about 2 orders of magnitude higher than wildfire emissions on average in a given category and, contrary to expectations, this applies even to the most sparsely populated areas. Anthropogenic emissions increase monotonically against population density up until 100 or more inhabitants $km^{-2}$, when emissions either saturate or slightly decrease (for CO, $PM_{2.5}$).

For wildfires, we see the highest emissions in the range 10 to 100 inhabitants $km^{-2}$ and the lowest in the most sparsely populated regions. We find that CO and $PM_{2.5}$ are the dominant pollutants emitted both by wildfires and human activities. The decline of total fire emissions towards dense population found in the GFED4.1s data (Fig. 1) is consistent with the SIMFIRE model, which predicts generally declining burned area with increasing population density. By contrast, the declining emissions from a peak at intermediate values towards low population values at first sight seem to contradict the assumptions made in SIMFIRE, which assumes burned area being largest in these low population regions. In some cases, there might only be a very small increase in burned with increasing population density at very low values of population density (ca. 3 inhabitants $km^{-2}$, Guyette et al., 2002). However, covariation of other environmental variables that drive fire occurrence with population density (Bistinas et al., 2014; Knorr et al., 2016b) explain why the more complex relationship seen in Fig. 1 is consistent with the model formulation of SIMFIRE. Furthermore, areas with fewer than three inhabitants $km^{-2}$ (see Appendix, Fig. A1) are all situated in boreal regions or northern highlands, with low fire occurrence (Giglio et al., 2013).

If we compare the two sources of emissions on a monthly instead of an annual basis and choose the month where wildfire emissions are highest, we find August climatological CO emissions for the area near Moscow – where large, devastating wildfires occurred in July and August 2010 (Kaiser et al., 2012) – to be of comparable magnitude to the climatological emissions of northern Portugal, with its large and frequent wildfire events (JRC, 2013). Even though the Russian fires were only one event in a 14-year record, they show up clearly in Fig. 2b around 54° N, 39° E (Moscow can be located by high anthropogenic emissions slightly to the west), as do the fires in the western Peloponnese in 2007 (Boschetti et al., 2008). $PM_{2.5}$ emissions of comparable magnitude are more widespread and are found again for Portugal and east of Moscow, but also along the western coastal regions of former Yugoslavia and Albania and southern Greece. The large forest fires in southern Europe (Pereira et al., 2005; Boschetti et al., 2008) and the 2010 fires east of Moscow all show peak emissions in August (Fig. 2c). If we sum over all wildfire emissions of the European study region (including western Russia) during June to October, the emissions also show a clear peak in August (Fig. 2f).

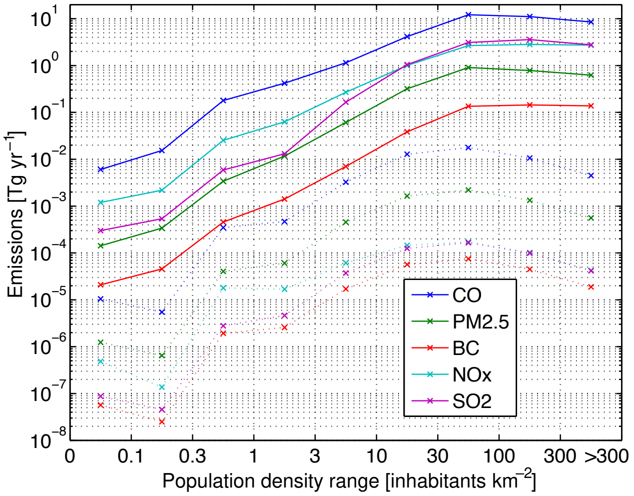

**Figure 1.** Current anthropogenic (solid lines) and wildfire emissions (dashed lines) for Europe by range of population density for various pollutants. Anthropogenic emissions are for 2010 and wildfire emissions average 1997–2014.

Of the regions and countries analysed (Table 3), Portugal clearly stands out, representing not only around 27 % of European wildfire emissions (here of $PM_{2.5}$, but relative results are similar for other pollutants), its emissions are also more than one order of magnitude higher per area than the European average (Pereira et al., 2005; JRC, 2013). Other countries or regions with high emissions per area are Russia (20 %), former Yugoslavia & Albania (9 %), Spain (16 %) and Greece (4 % of European emissions), and these countries together contribute as much as 77 % of total European $PM_{2.5}$ wildfire emissions using the GFED4.1s data. Most of the remainder is made up of Italy, France, Ukraine and Belarus (18 % of total), while northern European countries emit marginal quantities of fire emissions especially relative to the anthropogenic emissions.

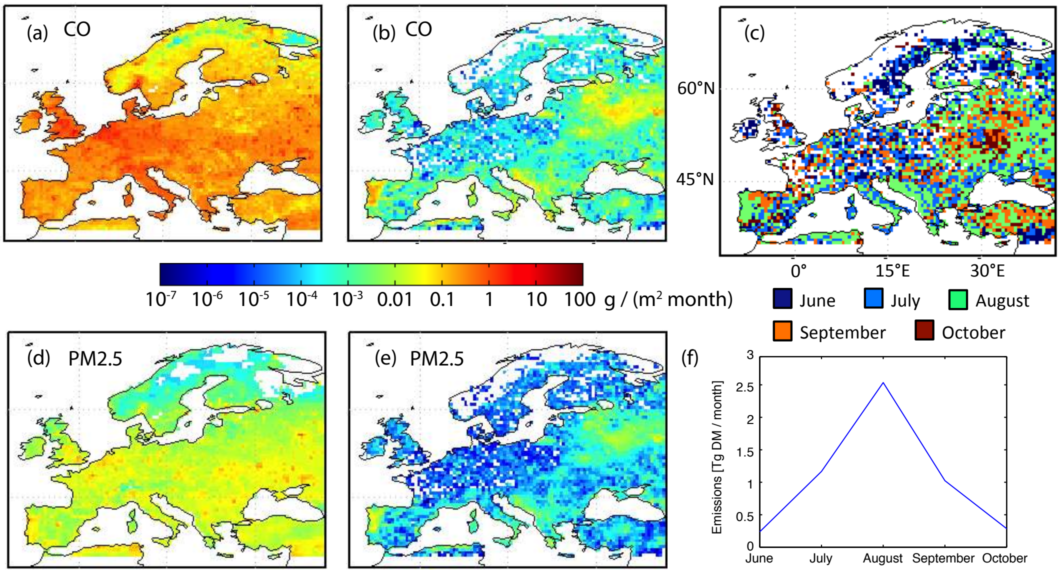

**Figure 2.** Emissions of CO **(a, b)** and $PM_{2.5}$ **(d, e)** from anthropogenic sources **(a, d)** and wildfires **(b, e)** during peak month of fire season **(c)**. Total wildfire emissions climatology 1997–2014 **(f)** in dry mass per month during the fire season for the European study. White: zero emissions.

**Table 3.** Changes in simulated $PM_{2.5}$ emissions for regions used in the analysis.

| Country/region | GFED4.1s mean 1997–2014 emissions | | Simulated emission changes 2010 to 2050 [%] | | | | | | Simulated emission changes 2010 to 2090 [%] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | RCP4.5 ensemble | | | RCP8.5 ensemble | | | RCP4.5 ensemble | | | RCP8.5 ensemble | | |
| | [Gg yr$^{-1}$] | [g (ha yr)$^{-1}$] | min. | mean | max. | min. | mean | max. | min. | mean | max. | min. | mean | max. |
| Austria | 3 | 0.5 | −15 | 15 | 51 | −4 | 32 | 77 | −3 | 47 | 146 | −16 | 81 | 213 |
| Belarus | 232 | 18.4 | 0 | 19 | 51 | −1 | 20 | 43 | −4 | 27 | 60 | 2 | 56 | 155 |
| BeNeLux | 13 | 2.6 | −43 | 27 | 164 | −28 | 45 | 235 | −71 | 120 | 537 | −49 | 209 | 828 |
| Bulgaria | 96 | 12.2 | −8 | 27 | 47 | 6 | 32 | 68 | 12 | 44 | 75 | 32 | 82 | 156 |
| Czech Republic | 7 | 1.0 | −8 | 55 | 138 | −21 | 57 | 212 | 16 | 182 | 611 | −2 | 212 | 800 |
| Denmark | 1 | 0.3 | −32 | 27 | 180 | −34 | 13 | 73 | −64 | 26 | 132 | −49 | 44 | 197 |
| Estonia | 9 | 5.2 | −17 | 4 | 28 | −35 | −1 | 37 | −26 | 4 | 40 | −27 | 18 | 84 |
| Finland | 8 | 0.4 | 0 | 8 | 21 | −5 | 5 | 16 | −1 | 10 | 21 | −16 | −1 | 28 |
| France | 154 | 4.2 | −13 | 15 | 62 | 0 | 26 | 59 | −16 | 23 | 90 | 2 | 69 | 169 |
| Germany | 44 | 1.7 | 4 | 45 | 121 | 18 | 62 | 138 | 7 | 126 | 426 | 30 | 201 | 657 |
| Greece | 277 | 20.9 | −13 | 30 | 76 | −11 | 25 | 80 | −9 | 31 | 77 | 20 | 78 | 211 |
| Hungary | 8 | 2.2 | −12 | 14 | 46 | −20 | 19 | 91 | −21 | 48 | 161 | −26 | 67 | 170 |
| Ireland | 1 | 1.1 | −21 | 5 | 32 | −7 | 20 | 56 | −30 | 29 | 107 | −6 | 54 | 157 |
| Italy | 425 | 14.6 | −4 | 41 | 97 | −29 | 46 | 179 | −14 | 70 | 197 | −7 | 124 | 301 |
| Latvia | 9 | 5.0 | −1 | 20 | 66 | 5 | 26 | 61 | −13 | 23 | 48 | 15 | 49 | 114 |
| Lithuania | 4 | 4.1 | −5 | 20 | 110 | −25 | 22 | 73 | −22 | 22 | 84 | −10 | 38 | 163 |
| Norway | 4 | 0.3 | 8 | 21 | 40 | 6 | 26 | 42 | 11 | 29 | 46 | 10 | 42 | 82 |
| Poland | 21 | 1.3 | 21 | 32 | 46 | 6 | 36 | 61 | 34 | 61 | 115 | 39 | 99 | 178 |
| Portugal | 1706 | 182.2 | 0 | 23 | 42 | 2 | 34 | 68 | 2 | 41 | 85 | 50 | 93 | 143 |
| Romania | 37 | 5.3 | 14 | 48 | 83 | 10 | 61 | 144 | 38 | 103 | 231 | 55 | 140 | 303 |
| Russia (west of 40° E) | 1276 | 31.7 | 0 | 9 | 19 | −11 | 5 | 24 | −14 | 8 | 22 | −16 | 13 | 52 |
| Slovakia | 4 | 2.7 | −18 | 30 | 106 | 0 | 45 | 127 | 8 | 104 | 256 | −1 | 140 | 415 |
| Spain | 987 | 24.3 | 3 | 18 | 38 | 4 | 20 | 46 | 11 | 36 | 70 | 33 | 68 | 119 |
| Sweden | 35 | 0.9 | −4 | 11 | 27 | −3 | 10 | 33 | −6 | 15 | 41 | −3 | 20 | 45 |
| Switzerland | 2 | 1.0 | −18 | 42 | 152 | −20 | 71 | 218 | −16 | 140 | 390 | −20 | 256 | 833 |
| Ukraine | 339 | 9.3 | 2 | 29 | 62 | −17 | 33 | 98 | −5 | 41 | 120 | 24 | 80 | 215 |
| United Kingdom | 10 | 1.6 | −11 | 20 | 94 | −10 | 22 | 82 | −15 | 35 | 124 | 8 | 67 | 167 |
| Yugoslavia & Albania | 581 | 25.4 | −4 | 34 | 79 | 5 | 38 | 80 | 14 | 57 | 131 | 38 | 95 | 185 |
| Europe | 6297 | 14.1 | 10 | 17 | 32 | 7 | 18 | 30 | 12 | 27 | 48 | 17 | 46 | 85 |

### 3.2 Predicted changes in wildfire emissions

Simulated wildfire emissions of $PM_{2.5}$ from Europe (Fig. 3) show a minor decrease over the 20th century, which is consistent with the lack of evidence for a change in European fire activity discussed in Sect. 1.2. Between 2000 and 2050, both climate scenarios show a similar slight increase with almost no discernible impact of the specific choice of population scenario. Only after 2050, simulations with a high climate change scenario (RCP8.5) show a marked increase, including a doubling of current emission levels for the highest ensemble members, while for RCP4.5, emissions barely increase any further. Differences between population scenarios have only a small impact on emissions in Europe, with SSP5 leading to the lowest, and SSP3 population and urbanisation to the highest emissions.

The SSP5 scenario assumes high levels of fertility, life expectancy and net immigration for western Europe under optimistic economic prospects, but opposite demographic trends, similar to developing countries, in eastern Europe. By contrast, SSP3 assumes slow economic development in a fragmented world with low migration, fertility and life expectancy, and therefore low population growth for the developed world, including Europe. As a result, projected wildfire emission trends differ greatly from those for the global scale, where emissions are dominated by demographic trends in developing countries (Knorr et al., 2016a), with SSP5 leading to the highest emissions. The reason for the difference is that in developing countries under SSP5, low population growth and fast urbanisation both lead to lower population in rural areas, thus increasing fire emissions. In developed countries, higher population growth leads to lower but slower urbanisation to higher emissions. Because Europe is already highly urbanised and the scope for further urbanisation small, the population growth effect dominates over the urbanisation effect and as a result SSP5 has the lowest emissions. The exact opposite happens for SSP3.

Portugal, with the highest emissions currently (Table 3), is estimated to retain its top position and experience with a 23 to 42 % increase in $PM_{2.5}$ emissions by 2050, depending on the climate scenario. For 2090 and high levels of climate change (RCP8.5), the ensemble average (over eight GCMs and three SSP scenarios) indicates almost a doubling of emissions (93 %), with the highest ensemble estimate reaching +134 %. By comparison, western Russia is simulated to experience only small emission increases or even a decrease. Spain, France, Italy, former Yugoslavia & Albania and Greece have similar increases in emissions to Portugal, all but Spain and France show extremely high ensemble maxima for 2090 that amount approximately to a tripling or quadrupling (Italy) of emissions by that point in time. Some countries or regions, like Benelux, Germany, Czech Republic and Switzerland, have even higher ensemble-mean estimated relative increases and ensemble maximum increases for RCP8.5 that represent an upward shift of almost an order of magnitude. However, these regions have very low wildfire emissions currently, making them unlikely to contribute significant total pollutant emissions in the future. A more important result is therefore that ensemble maxima for some of the strongly emitting regions are also very high. For example, the simulations indicate that Portugal could more than double, Greece triple and Italy quadruple its wildfire emissions until around 2090 for the RCP8.5 climate change scenario (Table 3).

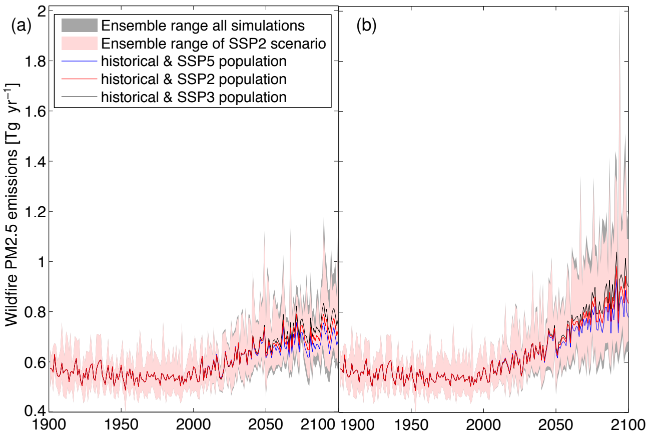

**Figure 3.** Ensemble means and ranges of simulated $PM_{2.5}$ emissions for all European regions for RCP4.5 **(a)** and RCP8.5 **(b)**. Historical population data are used for 1901 to 2005 and different SSP population scenarios for the remaining period.

Results of the sensitivity study using the alternative SIMFIRE parameterisation are shown in the Appendix (Fig. A3, Table A1). For all European regions, LPJ-GUESS-SIMFIRE simulates ca. 30 % lower burned area compared to the standard parameterisation, an offset that is rather stable across the simulation period, leading to a small impact on relative changes in emissions (Table A1, bottom row). On a region/country basis, however, the differences can be quite large, especially for changes from 2010 to 2090 and the RCP8.5 scenario. For example, using the Max-Planck Institute (MPI) climate model and the MCD45 parameterisation, Greece is predicted to increase wildfire carbon emissions by 350 % compared to +209 % for the standard parameterisation and +211 % for $PM_{2.5}$ and the ensemble maximum (Table 3).

### 3.3 Future patterns of exposure and interaction with population density

The character of the wildfire emission – population density relationship (Fig. 1), which largely follows the relationship for anthropogenic emissions but with a smaller magnitude of more than 2 orders, makes it improbable that wildfires could ever become a significant source of air pollution in Europe in even the more remote areas of Europe. In fact, even when we compare the highest case for wildfire emissions, combin-

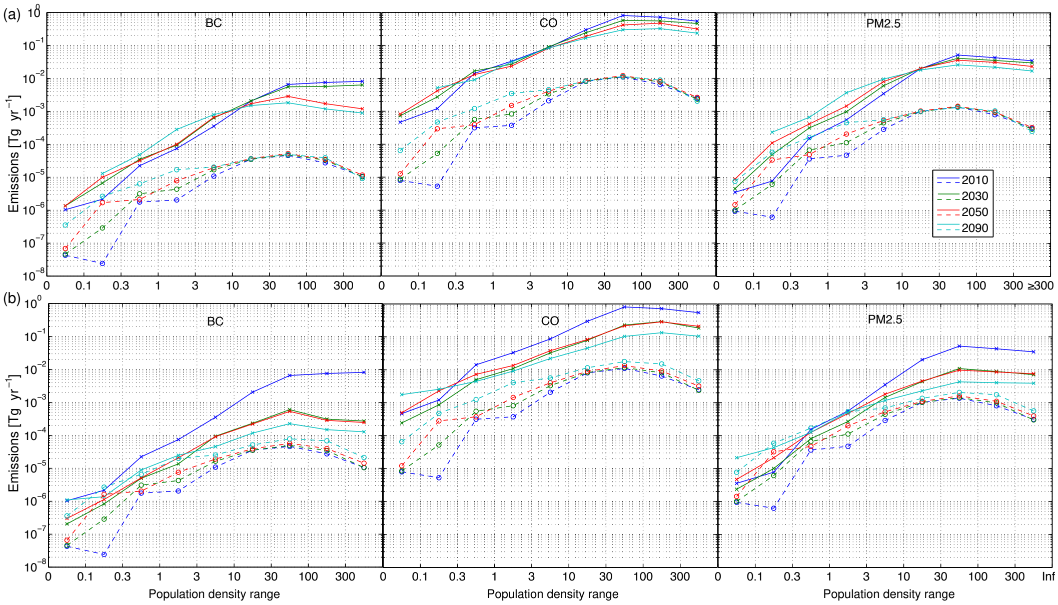

**Figure 4.** Monthly anthropogenic (solid lines, crosses) and wildfire emissions (dashed lines, circles) of selected pollutants for Europe during peak fire season by range of population density for different time windows and the SSP5 population scenario. **(a)** RC4.5 with current legislation anthropogenic emissions. **(b)** RCP8.5 with maximum feasible reductions anthropogenic emissions.

ing high RCP8.5 climate and $CO_2$ change with SSP3 rapid population decline over large parts of Europe (Fig. A2), with the scenario of maximum feasible reduction (MFR) in anthropogenic emissions, European wildfire emissions always remain much below those from anthropogenic sources (see Appendix, Fig. A4; this case would require that most greenhouse gas emissions leading to RCP8.5 would have to originate outside of Europe).

Monthly wildfire CO and $PM_{2.5}$ emission rates during the peak fire season, however, may come close to those from anthropogenic sources for regions with population densities between 3 and 100 inhabitants km$^{-2}$ (Fig. 4). In this case, we combine both RCP4.5 (Fig. 4a) and RCP8.5 (Fig. 4b) with the SSP5 scenario (fast urbanisation and high population growth, or slow decline in eastern Europe), so that differences in simulated wildfire emissions between the two subfigures are solely due to differences in the degree of climate and $CO_2$ change. It has to be taken into account that the population scenario used by the GAINS projections of anthropogenic emissions are different from the SSP scenarios used here, which were not available at that time (Stohl et al., 2015; Jiang, 2014). The climate and $CO_2$ effect, and in some areas population decline, lead to higher wildfire emissions compared to the present day. For RCP4.5, however, the increase is confined to areas with less than 10 inhabitants km$^{-2}$, caused mainly by widespread abandonment of remote areas due to increasing population concentration in cities under the SSP5 fast-urbanisation scenario (Fig. A2), leading to increases in the areal extent of the sparsely populated regions (translating into higher emission in that category even if per area emissions stayed the same). For RCP8.5, there is also a marked emission increase by 2090, consistent with Fig. 3b, which occurs across the entire range of population densities. For the CLE scenario, which we compare with RCP4.5/SSP5, wildfire BC and CO emissions always remain more than one order of magnitude below anthropogenic emissions for all population density categories, even at the peak of the fire season. For $PM_{2.5}$, wildfire emissions may reach around 10 % of the anthropogenic counterpart for less than 10 inhabitants km$^{-2}$. Even for MFR (Fig. 4b), CO from wildfires remain a minor source, but for BC and $PM_{2.5}$ (except for the most densely populated regions), wildfires reach anthropogenic-emission levels. While on a long-term annual basis, wildfire emissions are unlikely to develop into an important source of air pollution for Europe as a whole, some areas already have comparatively high emissions (Fig. 2). A spatially explicit analysis of future emissions again using RCP8.5, SSP5 population and MFR anthropogenic emissions, reveals that by 2090 wildfires could become the dominant source of BC for much of Portugal (Fig. 5a). For $PM_{2.5}$ in Portugal or BC and $PM_{2.5}$ in boreal regions, this could already be the case as soon as these maximum feasible emission reductions have been achieved (2030). CO is only likely to play an important role in Portugal, but only by 2090 because of large increases in wildfire emissions due to high levels of climate change.

During the peak of the fire season (Fig. 5b), in 2030 fire emissions dominate for most of Portugal, coastal regions of former Yugoslavia and Albania, western Greece plus some scattered parts of Spain, Italy and Bulgaria as well as the northern part of eastern Europe (Russia, Ukraine, Belarus),

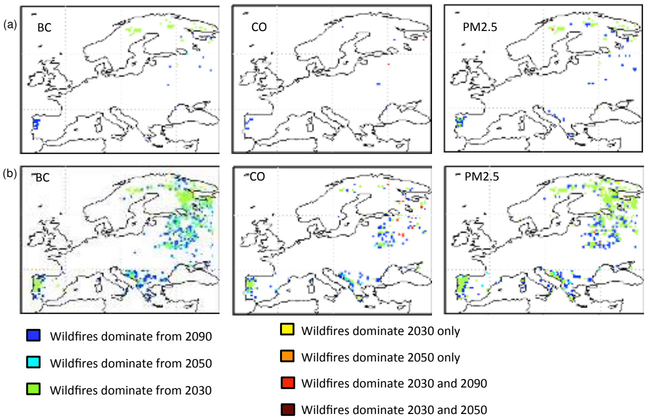

**Figure 5.** Areas where wildfire emissions exceed anthropogenic emissions in 2030, 2050 or 2090 on annual basis **(a)** or during peak fire season **(b)** (month of maximum wildfire emissions varying by grid cell), assuming RCP8.5 climate, SSP5 population and maximum feasible reduction anthropogenic emissions.

as soon as maximum feasible reduction of anthropogenic emission reductions are implemented – considering that by 2030 the degree of climate-driven increases will be minimal. The areas affected more strongly are predicted to increase further by 2050, especially for BC in north-eastern Europe, and by 2090 in particular in southern Europe.

These results may change when a different anthropogenic emissions data set is chosen. There are, for example, considerable differences between the present scenario, assuming half of 2050 ECLIPSE GAINS 4a emissions by 2090 and the PEGASOS BPL v2 emissions for the same year. For example, PEGASOS has much lower CO emissions in north-western Russia and Finland, but our extended ECLIPSE data set lower emissions in the southern Balkans, which would affect results shown in Fig. 5b. In general, however, there is a reasonable agreement between the two scenarios. Only when MFR is combined with assumed further technical advancement and a stringent climate policy, (PEGASOS scenario 450-MFR-KZN, see Table 1) emissions are projected to fall even further by 2090. In this case, however, we also expect smaller increases in wildfire emissions due to limited climate change. Another important point to consider in further studies is that atmospheric aerosols from anthropogenic pollutant emissions itself have either a cooling (Ramanathan et al., 2001) or warming (Ramanathan and Carmichael, 2008) effect on climate, and also influence plant productivity (Mercado et al., 2009), creating potentially important cross links and feedback between air pollution and wildfire emissions.

## 3.4 Policy relevance of results

Our analysis shows that the importance of wildfire emissions as source of air pollution will further increase, especially given a scenario of strong climate change, but also that the main reason is likely to be a reduction in anthropogenic emissions. It is therefore mainly a combination of climate warming and strong reduction in anthropogenic emissions that could make wildfire emissions a significant contributor to air pollution during the fire season. This could mean that fire management will have to be improved in the areas concerned if air quality targets are to be met.

In order to be relevant for air pollution policy, wildfires must (1) contribute a considerable fraction of pollutant emissions and (2) the emissions need to be large enough so that limit values of air pollutant concentrations are exceeded. Modelling air pollutant emissions from wildfires in Europe remains a challenge for science and policy alike, from an observational and even more so a modelling standpoint. Observing present-day patterns and their changes, and the attribution of observed changes to climate change or socio-economic drivers is difficult, which makes it also hard to provide reasonable future projections. Current wildfire emission estimates are also uncertain owing to differences in burned area, emissions factors or the assumed fraction of combusted plant material, which could easily double or halve the emissions values when assumptions are modified (Knorr et al., 2012). Likewise, the uncertainty in the published range of even the present anthropogenic emissions is of similar relative magnitude, even though likely somewhat smaller than for wildfire emissions (Granier et al., 2011). However, given the large differences by orders of magnitude found at the European level, it is clear that air pollution from wildfire emissions presently and in most cases also in the future only plays a minor role in most of Europe under current conditions of air pollution.

Answering the question whether the importance of wildfire emissions has changed over the last century is difficult, but there is no strong evidence that this has been the case. The reason for the lack of evidence for climate-driven increases in European wildfire emissions may simply be that these emissions during the 20th century have tended to slightly decrease, due to socioeconomic changes, rather than increase, as several modelling studies suggest, including the present one.

For the future, however, fire emissions may become relatively important (condition 1) if stringent policy measures are taken to further limit anthropogenic emissions. The question of whether the magnitude can also reach levels sufficiently high to interfere with air quality policy aimed at limiting anthropogenic sources therefore remains. To illustrate this, we focus on the most relevant air pollutant component, PM$_{2.5}$. In the following, we derive an approximate threshold for peak-month wildfire PM$_{2.5}$ emissions ($E^{\mathrm{p.m.}}_{\mathrm{PM}_{2.5}}$) above which these might interfere with air quality goals. According to Fig. 2e, the highest emissions in central and northern Portugal are around 0.05 g m$^{-2}$ during the peak month. Assuming that the peak month contributes about half the annual wildfire emissions (Fig. 2f), a boundary layer height $h = 1000$ m (as a compromise between night and day time) and a life time of the emissions of $\tau = 1/50\,\mathrm{yr}$ (7.3 days), and that the impact on mean annual mean (not peak-month) $PM_{2.5}$ concentrations corresponds roughly to the steady state concentrations, $C_{PM_{2.5}}$, with $E^{\mathrm{p.m.}}_{PM_{2.5}} = 0.05\,\mathrm{g\,(m^2\,month)^{-1}}$, we obtain:

$$\begin{aligned} C_{PM_{2.5}} &= E^{\mathrm{p.m.}}_{PM_{2.5}} \times 2\ \mathrm{months\ year}^{-1} \times \tau/h \\ &= 0.05 \times 40\,\mu\mathrm{g\,m^{-3}} \\ &= 2\,\mu\mathrm{g\,m^{-3}}. \end{aligned} \tag{1}$$

During the peak fire month, this would amount to six times this level, i.e. $12\,\mu\mathrm{g\,m^{-3}}$ (half of the amount emitted in 1/12 of the time). For 2012, most air quality stations in central to northern Portugal report mean annual $PM_{2.5}$ values of up to $10\,\mu\mathrm{g\,m^{-3}}$ (EEA, 2014, Map 4.2). Fire activity during that year was moderately below average, with around 80 % of the long-term average burned area (JRC, 2013). Assuming burned area to scale with emissions, we would expect 80 % of the long-term average pollutant level (Eq. 1), i.e. $0.8 \times C_{PM_{2.5}} = 1.6\,\mu\mathrm{g\,m^{-3}}$ as the wildfire contribution for 2012 in the areas with the highest emissions, which would be consistent with the reported air quality data.

If the European Union in the future moved from its own air quality target of $25\,\mu\mathrm{g\,m^{-3}}$ annual average (EEA, 2014) to the more stringent World Health Organization guideline of $10\,\mu\mathrm{g\,m^{-3}}$ (WHO, 2006), a contribution of $3\,\mu\mathrm{g\,m^{-3}}$ would probably be considered policy relevant, as it could bring the total concentration above the WHO target. According to Eq. (1), such annual mean levels would require roughly an emissions of $0.07\,\mathrm{g\,m^{-2}}$ $PM_{2.5}$ emissions during the peak fire month, which we adopt as a practical lower threshold for when these emissions might become relevant for meeting air quality policy goals. According to Fig. 6, such levels are currently not met and indeed central to northern Portugal has air quality readings that are towards the lower end of European air quality measurements (EEA, 2014). However, such conditions could be met later during this century with high levels of climate change. For the remaining European areas with high wildfire emission, the emissions are likely to remain below this threshold according to the present estimate.

We also estimate that for Europe, ozone ($O_3$) produced from wildfire emissions as a secondary air pollutant (Miranda et al., 2008; Jaffe and Widger, 2012) is and will remain below levels that make it relevant for air quality targets. Using a ratio of 3 : 1 for CO to $O_3$ production for temperate North America, CO emissions for Portugal from Fig. 2 and a similar residence time than for $PM_{2.5}$ (Jaffe and Widger, 2012), we estimate a wildfire contribution to the $O_3$ average concentration for Portugal in August of $0.4\,\mu\mathrm{g\,m^{-3}}$, one fifth of the corresponding value for $PM_{2.5}$ (Eq. 1). On the other hand, the WHO 8-hour limit of $100\,\mu\mathrm{g\,m^{-3}}$ $O_3$ is four times higher than the 24-hour WHO limit for $PM_{2.5}$ ($25\,\mu\mathrm{g\,m^{-3}}$).

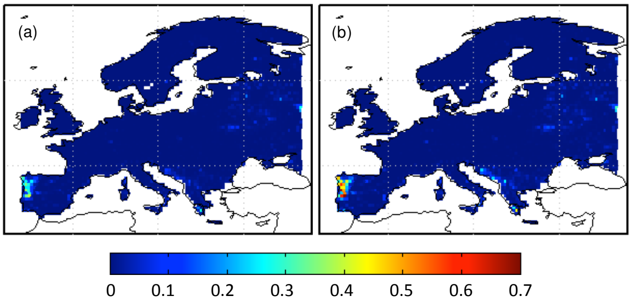

**Figure 6.** Wildfire $PM_{2.5}$ emissions during peak fire season displayed on linear scale, in $\mathrm{g\,(m^2 month)^{-1}}$: **(a)** current and **(b)** 2090.

## 4 Summary and conclusions

- The evidence for changes in fire regimes in Europe for the past several decades is not clear enough to attribute any changes to climatic drivers. A certain role of land abandonment leading to larger fires and higher fire frequency is often reported but has not been universally demonstrated.
- Confidence in future predictions of fire emissions for Europe is generally low. This is partly because important factors such as changes in emission factors or fuel combustion completeness have never been taken into account. Another reason is that model-based simulations of fire emissions in Europe cannot be properly validated because the multi-decadal data are too ambiguous. Finally, there is no consensus about the main drivers of fire frequency and in particular the way land use impacts average fire size. This caveat is also valid for the following statements.
- Future demographic trends are an important factor for fire emissions especially for emerging areas of low population density.
- For Europe, only a moderate increase in fire emissions is plausible until 2050. However, a doubling of fire emissions between now and the late 21st century is possible under higher climate change/$CO_2$ emissions trajectories. For some southern European countries, uncertainties are higher and the tripling or even quadrupling of emissions appears plausible, even if unlikely.
- The highest ratio of wildfire to anthropogenic emissions for CO, BC and $PM_{2.5}$ is found for Portugal. During the fire season, emissions of these pollutants might already exceed those from anthropogenic sources. Emissions are generally projected to increase further with climate change.
- If air pollution standards are further tightened, in large parts of the Mediterranean and north-eastern Europe, wildfires could become the main source of air pollution

during the fire season, unless improved fire management systems are considered.

- Other regions could still emit enough pollutants from wildfires to be policy relevant, either seasonally or on an annual basis if meteorological conditions are more conducive to high pollutant concentrations as it is implied in the calculation above, or if the emissions or emission change estimates used in the present study turn out to be on the low side.

## Data availability

CRU TS 3.21 climate observations are available from the British Atmospheric Data Centre at http://browse.ceda.ac.uk/browse/badc/cru/data/cru_ts/cru_ts_3.21, RCP historical and scenario $CO_2$ concentrations from the Institute of Applied Systems Analysis (IIASA) at http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=download, population density data according to HYDE 3.1 from PBL at http://themasites.pbl.nl/tridion/en/themasites/hyde/download/index-2.html, SSP population and urbanisation scenarios by country from IIASA at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=countries, GFED 4.1s fire emissions from the Free University of Amsterdam at http://www.falw.vu/~gwerf/GFED/GFED4/, and ECLIPSE GAINS 4a and PEGASOS PBL global anthropogenic emissions from the ECCAD web portal at http://eccad.sedoo.fr/eccad_extract_interface/JSF/page_login.jsf.

## Appendix A

Table A1. Sensitivity of predicted emission changes to SIMFIRE parameterisation.

| Country/region | Ensemble emission changes 2010 to 2050 [%] | | | | Ensemble emission changes 2010 to 2090 [%] | | | |
|---|---|---|---|---|---|---|---|---|
| | RCP4.5 | | RCP8.5 | | RCP4.5 | | RCP8.5 | |
| | std.[a] | MCD45[b] | std. | MCD45 | std. | MCD45 | std. | MCD45 |
| Austria | −6 | −37 | 6 | −7 | 26 | 2 | 45 | 26 |
| Belarus | 18 | 6 | 18 | 5 | 35 | 17 | 45 | 33 |
| Benelux | 30 | 29 | 20 | 19 | 61 | 46 | 129 | 107 |
| Bulgaria | 50 | 35 | 21 | 20 | 75 | 56 | 146 | 73 |
| Czech Republic | 11 | 45 | 15 | 19 | 69 | 128 | 58 | 108 |
| Denmark | −7 | −3 | 44 | 57 | 33 | 18 | 81 | 43 |
| Estonia | −11 | −21 | −35 | −2 | −15 | 15 | −18 | −8 |
| Finland | 6 | 27 | −3 | −9 | 2 | 13 | −13 | −17 |
| France | −1 | 7 | 27 | 22 | 8 | 21 | 78 | 77 |
| Germany | 21 | 14 | 50 | 30 | 96 | 60 | 155 | 107 |
| Greece | 85 | 35 | −3 | 52 | 35 | 56 | 209 | 350 |
| Hungary | 41 | 38 | 36 | 4 | 92 | 69 | 98 | 56 |
| Ireland | −7 | −16 | 10 | −9 | −17 | −21 | 38 | 8 |
| Italy | 72 | 93 | 73 | 45 | 77 | 111 | 165 | 146 |
| Latvia | 23 | 23 | 25 | 36 | 23 | 23 | 16 | 36 |
| Lithuania | −2 | −12 | 12 | −9 | 28 | 4 | 26 | 25 |
| Norway | 6 | 11 | 2 | 9 | 23 | 24 | 15 | 38 |
| Poland | 35 | 22 | 28 | 33 | 106 | 67 | 87 | 57 |
| Portugal | 104 | 89 | 94 | 193 | 128 | 115 | 218 | 164 |
| Romania | 70 | 34 | 68 | 25 | 117 | 55 | 166 | 131 |
| Russia | 5 | 7 | −2 | −1 | −1 | 6 | 7 | 11 |
| Slovakia | 27 | 9 | 42 | 57 | 129 | 79 | 133 | 115 |
| Spain | 30 | 26 | 34 | 90 | 82 | 100 | 134 | 157 |
| Sweden | 1 | −2 | 3 | 2 | 16 | 8 | 13 | 10 |
| Switzerland | 58 | 31 | 101 | 44 | 202 | 71 | 310 | 168 |
| Ukraine | 28 | 18 | 32 | 20 | 55 | 39 | 79 | 56 |
| United Kingdom | 12 | 14 | 45 | 35 | 24 | 32 | 70 | 65 |
| Yugoslavia & Albania | 71 | 47 | 35 | 24 | 114 | 71 | 116 | 69 |
| Europe | 21 | 19 | 19 | 28 | 40 | 41 | 65 | 64 |

[a] SIMFIRE standard parameterisation with MPI climate model output.

[b] SIMFIRE optimised against MCD45 global burned area product, also with MPI climate model output.

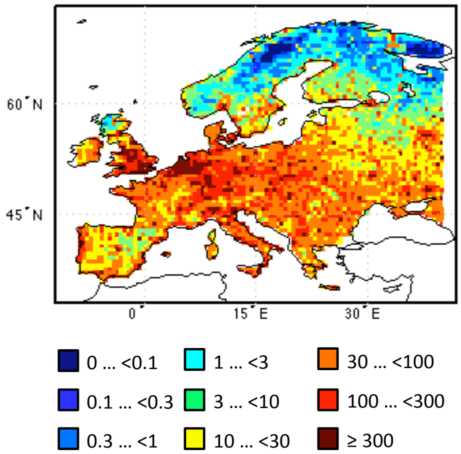

**Figure A1.** Current (2010) population density (inhabitants $\mathrm{km}^{-2}$) in Europe by ranges considered in the analysis. Derived from gridded observed 2005 values extrapolated to 2010 using SSP2.

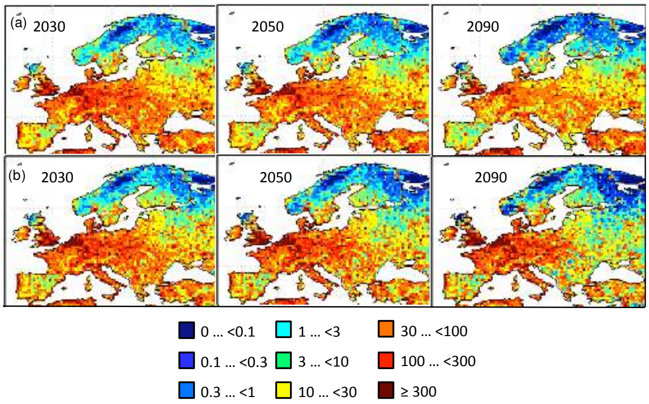

**Figure A2.** Projected population density (inhabitants $\mathrm{km}^{-2}$) in Europe: **(a)** SSP3 and **(b)** SSP5.

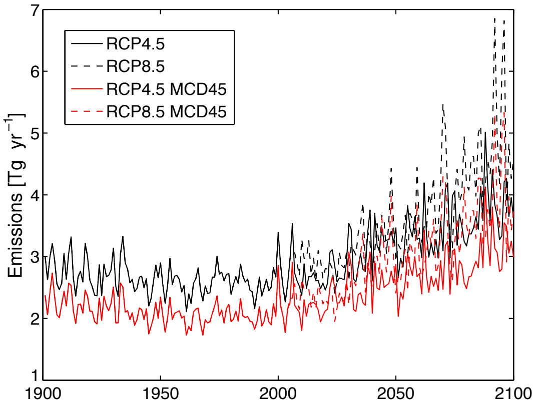

**Figure A3.** Wildfire carbon emissions for all European regions with the standard SIMFIRE parameterisation compared to runs using SIMFIRE optimised against MCD45 global burned area, for two RCP scenarios and simulations using the MPI global climate model.

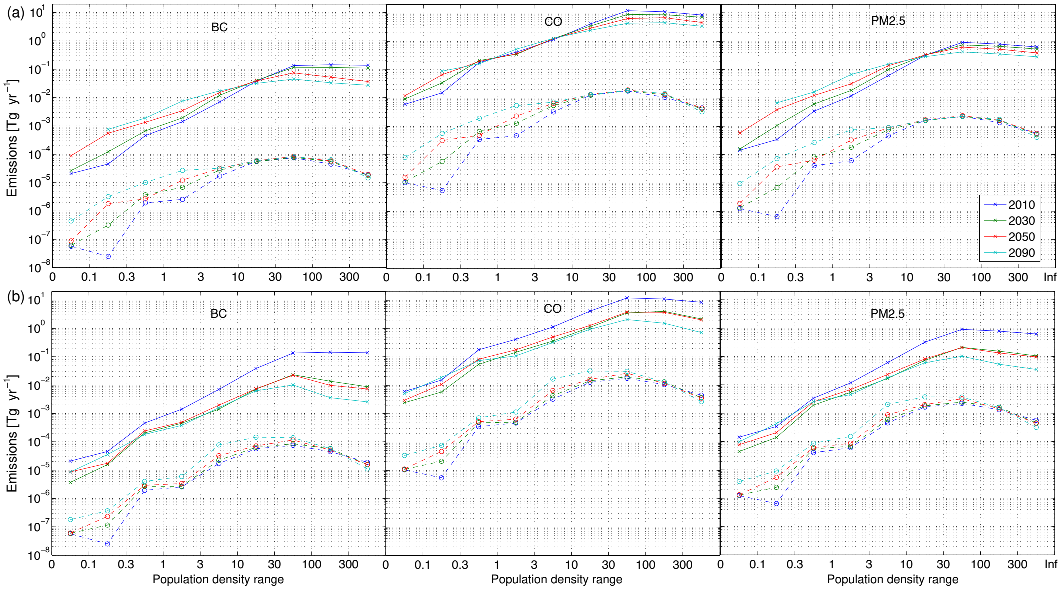

**Figure A4.** Annual anthropogenic (solid lines, crosses) and wildfire emissions (dashed lines, circles) for Europe by range of population density for selected pollutants and time windows. **(a)** RCP4.5 climate, SSP5 population and current legislation (CLE) for anthropogenic emissions; **(b)** RCP8.5 climate, SSP3 population and maximum feasible reduction (MFR) for anthropogenic emissions.

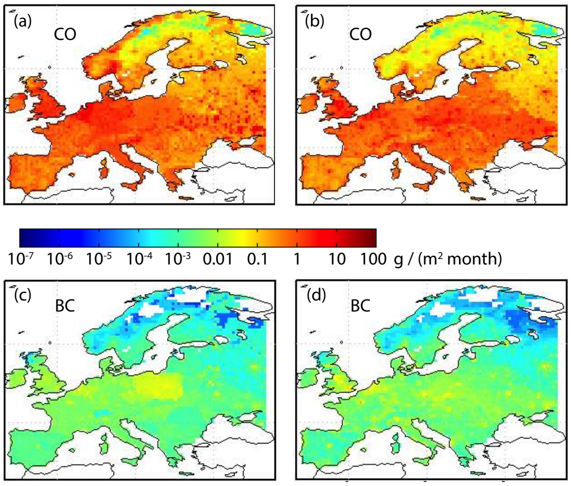

**Figure A5.** Comparison of annual anthropogenic CO and BC emissions for 2090: **(a, c)** 50 % of ECLIPSE GAINS 4a MFR for 2050 as assumed for 2090 in present study and **(b, d)** PEGASOS PBL v2 MFR-KZN.

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