Author reply: Climate changes and wildfire emissions of atmospheric pollutants in Europe by W. Knorr et al.

Referee comments in italics

We would like to thank both referees for their thorough reading of the manuscript and for their very detailed, constructive and useful comments, which show their dedication to improving this manuscript.

Response to comments by anonymous referee #1

1) The relatively new aspect is thereby the combined assessment of anthropogenic emissions and wildfire emissions and the assessment of air quality impacts. This should be reflected more in the title of the manuscripts.

Reply: We had thought a lot about the title, which needs to describe a chain of events: climate change driving changes in wildfire occurrence driving changes in emissions. We suggest to change the title to "Air quality impacts of European wildfire emissions in a changing climate". We believe including the comparison with anthropogenic emissions in the title would make it too long.

2) The manuscript reads in part a bit lengthy and could be shortened (e,g, the discussion on the pros and cons of different fire models). In parts I was confused whether model results or GFEDv4 is discussed.

Reply: See reply to referee #2's comment 2), which contained detailed suggestions on this point. One aim of the manuscript is to provide a review of the status of fire scenario modelling in Europe, as such a review is not currently available in the literature. We chose to include this in a paper on future emissions rather than a separate review paper because we believe that the former sets the context for the latter. To help the reader we provide sub-headings of Section 1, so that parts of the introduction can be skipped.

We have further clarified this by moving the statement contained in the last paragraph of Subsection 1.1 to the start of Section 1, before the first sub-heading (1.1). The text has been revised in order to make it more suitable for serving as the start of the Introduction.

3) Fire model results are used to scale satellite based observed burned area (GFEDv4) into the future. The scaling is done on a country basis. Countries are not related to fire occurrence. Does averaging on a country basis impact your results? Also I was wondering whether SIMFIRE does actually produce fires in all regions of Europe, i.e. do you get a scaling factor for each country in Europe? Here it would also be helpful to show how SIMFIRE actually compares to GFEDv4 in Europe.

Reply: A detailed comparison of SIMFIRE with GFED is provided by Wu et al. (2015). We have added the following sentence at the end of paragraph 1 of Section 2:

"A comparison of LPJ-GUESS-SIMFIRE burned area for Europe against 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."

Fire occurrence is driven to a considerable degree by management practice (Moritz et al. 2014), as can be seen for example when comparing burned area in Finland with that in north-western Russia (Fig. 2 in Knorr et al. 2014). We therefore scale simulated emissions for every pixel in a given country by a uniform scalar.

The reviewer is right that in some cases, the model might not simulate any fire for a given countries. This is indeed the case for Moldova, which we have excluded from the analysis because the prediction did not yield valid results (see Table 3). We have added a statement to explain this in the new Section 2.4, first paragraph. "reading what?"

4) What about future landuse change? Is this considered in SIMFIRE?

Reply: SIMFIRE considers human impact through a statistical approach related to population density, which includes land use. Since the simulations are based on a model trained on recent data, we implicitly assume that the relationship between land use practice and population density is invariant over time. A statement has been added to clarify this to the first paragraph of Section 2:

" The effect of changing land use is considered implicitly by the use of population density (Knorr et al. 2016a, b)."

5) Regarding the chemical species: Do you use the species provided by GFEDv4 and apply the emissions factors or Andreae and Merlet only to your model results, or are the emission factors applied to both? Is this consistent?

Reply: There is indeed a slight inconsistency here, which however does not affect the results. GFED uses emission factors by Akagi et al. 2011, but SIMFIRE those by Andreae and Merlet, albeit with a recent update (Knorr et al. 2012). Since from SIMFIRE we only use the spatio-temporal changes and not the absolute emissions, the only case where this could affect emissions is when the biome category of a pixel changes over time. Since, however, all of Europe is assigned "extra-tropical forest" for all of the simulation period, this does not affect the results and therefore the emission factors by Andreae and Merlet (and differences with Akagi) are eliminated in the scaling. In order to increase clarity, and because this is mathematically correct, we remove mention of the Andreae et al emission factors and explain the general scaling approach in the first paragraph of Section 2.

Minor comments

6) Line 155: were does the number two come from? Does this refer to Table1?

Reply: We had discarded Scholze et al. (2006), because it does not specifically show any burned area, but of course simulation of carbon emissions also implies simulation of burned area (usually). We have therefore replaced the sentence in question by:

"Most of the early predictions of future fire activity did not simulate burned area, with the exception of Scholze et al. (2006), which however only reports probability of change. For example, the pioneering ..."

7) Line 238: Emission factors by Andrea and Merlet: Many studies use emission factors by Akagi et al. For completeness it would be nice to document the emissions factors applied in this study and compare them to the one given by Akagi et al.

The emissions factors used do not influence the results, See reply under 5 for detailed information).

8) Line 308: Please explain the different Pegasus scenarios used in the Table.

Reply: These were explained in the footnotes of Table 2. We have added a reference to the table and moved the description to a separate column.

9) Line 355: Knorr et al. ? – please complete.

Reply: We meant to refer to Knorr et al. (in review), but this paper has now been accepted (Knorr et al. 2016b).

10) Line 355: Figure1/Figure2. Are the wildfire emissions in Figure1 and Figure 2 from SIMFIRE or from GFEDv4? I thought the climatological mean refers to GFEDv4. In this case, however, I do not understand the discussion on SIMFIRE here.

Reply: Correct, this is a discussion of GFEDv4.1s emissions, hence the average of 1997-2014. What was meant here was the peaked function describing average wildfire emissions against population density, where emissions first increase with population density despite of the result reported in Knorr et al. (2014) that burned area (driving emissions) almost always declines with increasing population density because the fire regime is ignition saturated (Guyette et al. 2002). This has to do with the fact that population density is also correlated with other factors driving burned area or emissions, e.g. plant productivity. A discussion of this is provided by Bistinas et al. (2014) and in Knorr et al. (2016b). We feel that a discussion of this and of ignition saturated fire regimes would be out of topic and we decided not to expand this here.

We have modified the text as follows (Section 3.1, first paragraph):

"The decline of total fire emissions towards dense population found in the GFED4.1s data (Figure 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 population density (ca. 3 inhabitants / km^2, Guyette et al. 2002). However, co-variation 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 Figure 1 is consistent with the model formulation. Furthermore, areas with fewer than 3 inhabitants / km^2 (see Appendix, Figure A1) are all situated in boreal regions or northern highlands, with low fire occurrence (Giglio et al. 2013)."

11) Line 359: Are the climatological means comparable for Portugal and Russia, or the single large wildfires events in these regions. Please clarify.

Reply: Yes, this was not clear. It refers to the climatological average, but during the respective peak month of the fire season, which is August for both. The amount is about 0.1g/(m^2 month) for the region around Moscow, and about 0.4 for northern Portugal. This is remarkable, as the Russian value is likely dominated by a single event, whereas

Portugal experiences frequent fire events, albeit with 2003 and 2005 more than twice the average annual burned area of 1980 to 2012 (JRC 2013).

We have reformulated the text to:

" ..., we find August climatological CO emissions for the area near Moscow – where large, devastating wildfires occurred in July and August 2010 (Kaiser et al. 2010) – to be of comparable magnitude to the climatological emissions of northern Portugal, with its large and frequent wildfire events (JRC 2013) ."

12) Line 372: I'm not sure I understand this. Fire emissions you have monthly, but anthropogenic emissions only annual? For the annual anthropogenic emissions the 'residential and commercial' sector is excluded when calculating the contribution of wildfire emissions in the peak burning season? Please clarify this.

Reply: Yes, anthropogenic emissions were only available on an annual basis. Therefore, we employ a simplified model of the seasonal cycle of anthropogenic emissions, which assumes that emissions from room heating in the 'residential and commercial' sector (which concerns only small-scale commercial installation and could be heating of office blocks or schools for example, but also gas cooking stoves, which we neglect here) are zero during the fire season, while other emissions have no seasonal cycle. Therefore, the average monthly anthropogenic emissions during the fire season equal (annual emissions - emissions from residential and small-scale commercial combustion) / 12. This has been clarified (last paragraph of Section 2).

13) Line 398: The paragraph on the relative importance of different regions for the total wildfire emissions in Europe would fit better into the previous section were the climatological mean is discussed and not so much in the 'predicted change' paragraph.

Reply: Thank you for the suggestion. We have moved the paragraph in question to the end of Section 3.2.

14) Line 424: Do these numbers refer to Table 3? Please, check.

Reply: The ensemble maximum (last column in Table 3) states +211% for Greece by 2090, +301% for Italy, and +143% for Portugal. This was probably an oversight, as the line below Portugal states +303% for Romania, an increase from a much lower base, though. We have corrected and clarified this:

"... indicate that Portugal cold more than double, Greece triple and Italy quadruple its wildfire emissions ... (Table 3)."

15) Line 449: Please rephrase this sentence.

Reply: Thank you, done:

"Monthly wildfire CO and PM2.5 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 (Figure 4)."

16) Line 458: Why doesn't the change in population contribute to the change in wildfire emissions?

Reply: Revised to:

" The climate and CO_2 effect, and in some areas population decline, lead to higher wildfire emissions compared to present day."

17) Line 466: How is this consistent with Figure 4?

Reply: Thank you for spotting this. The temporal change is consistent with Figure 3b. This has been corrected:

"For RCP8.5, there is also a marked emission increase by 2090, consistent with Figure 3b, which occurs across the entire range of population densities."

18) Line 473: Please rephrase. The paragraph could be moved to the discussion/conclusion.

Reply: We have moved the paragraph to the beginning of Section 3.4.

19) Line 506: A mfr for air pollutants does not necessarily relate to less climate change.

Reply: The sentence refers to the scenario MFR-KZN-450, which includes a 450ppm climate target (hence "stringent climate policy") in addition to MFR. See also reply to comment 8).

20) Line 546: boundary layer height

Reply: Thank you, corrected.

21) Line 561: reported

Reply: Corrected.

22) Line 559: I do not understand how derive 1.6 mug/m3.

Reply: 80% of the long-term average equilibrium concentration of 2 mug/m3, because 2012 had 80% of the long-term average burned area. This has been clarified.

23) Line 564: why do you consider a level of 3 mug/m3 and not 10 as the WHO does?

Reply: Because an additional contribution of 3mug/m3 from wildfires could bring the total concentration, including that caused by anthropogenic sources, over the WHO threshold. Added

"... , as it could bring the total concentration above the WHO target."

24) Line 574: This discussion might be better placed in the conclusion section.

Reply: Good suggestion. We have moved this so that it appears as the last bullet point of Section 4.

Response to comments by anonymous reviewer #2

1) Page 7, Line 160. "but also no change in fuel load". Incorrect statement. The Pechony and Shindell (2010) fire model does have a dependence on fuel load. I believe it is through sensitivity to changing LAI, but you may need to check the exact formulation with the developers.

Reply: Correct. Pechony and Shindell (2010) refer to Pechony and Shindell (2009) for methods. According to Equ. (3) therein, flammability (und thus number of fires) is influenced by vegetation density. However, the sentence in question states something else: that one would have to assume constant fuel load and average fire size to use projected numbers of fires as a proxy for future emissions. For clarity, it has been modified to:

"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 average size of fire."

2) The Methods section needs to be re-written/re-organized/untangled with sub- sections that describe which modeling exercise refers to which specific project goal. Many different datasets are introduced and it is hard to keep a track. At present, the reader is essentially left to work out which experiments and datasets are used for which task. For example, the anthropogenic and fire emissions comparison aspect involves the GFED inventory for present day, which is confusing because the study is initially presented as a dynamic fire prediction project.

Reply: The dynamic aspect of the study lies in the prediction of biomass combusted, not in the prediction of per-species emission, as in Knorr et al. (2016a). We believe that his has contributed greatly to the confusion and have therefore clarified this in the first paragraph of Section 2, and have removed mention of the SIMFIRE emission factors altogether (see detailed reply to comment 5 by reviewer #1).

In addition, we have re-structured Section 2, introducing sub-sections: 2.1) Simulations, 2.2) Model input data, 2.3) Data for current wildfire and anthropogenic emissions, and 2.4) Method of analysis.

3) On extension of this point (2), how does the present day dynamic fire prediction scheme compare with GFED inventory? I suspect these results are in one of the Knorr et al. papers but it is not clearly explained where and what is the status of the validation.

Reply: see reply to comment 3 of referee #1.

4) How was the CMIP5 data downscaled to 1x1 deg for the fire-vegetation model?

Reply: This was done as described in used the same data as Ahlström et al. (2012), which is explained in Knorr et al. (2016a), from where we use the dynamic emissions simulations. We have added this information to the present manuscript (end of first paragraph of new Section 2.2).

5) To the conclusion "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", what statistically robust physical climate changes have occurred in Europe over the period? What has happened to temperature and precipitation, and extreme meteorological events? For example, if not much actual climate change has occurred (yet), then it's obvious that there wouldn't be any climate-driven changes in fire regimes (yet).

Reply: The region 10°W to 40°E and 30 to 75°N ("Northern Europe" north of 48°N and "Mediterranean Basin" south of 48°N, Harris et al. 2014) has seen an upward temperature trend of 0.1°C/decade for 1901-2009 that is significant at the 95% level for both regions separately, which is also clearly visible in the annual data. There is also a significant upward precipitation trend for Northern Europe of 0.9 (mm/year) / decade. The downward trend for Mediterranean Basin is not significant for CRU, but significant for GPCC. A sentence has been added to the beginning of Section 1.2 to describe this:

"Since the beginning of the 20th century, climate in Europe as been warming by 0.1°C per decade, a trend that is significant at the 95% level. A 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 by between 0.3 and 0.5 mm per decade for southern Europe and Mediterranean Basin, where the higher estimate is also significant (Harris et al. 2014)."

In addition, a discussion of results from a recent publication (Turco et al. 2016) has been added to the last paragraph of Section 1.2:

"High-quality quantitative data on fire occurrence Europe-wide, recompiled in the European Forest Fire Information System (EFFIS), is only available starting from the 1980´s. 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 1970´s and 80´s (Turco et al., 2016). "

6) Page 22, Line 525. "Likewise, the uncertainty in the published range of even the present anthropogenic emissions is of similar relative magnitude". Is this true? Based on this and other studies, seems that uncertainty in wildfire emission estimates must be larger than for anthropogenic sources?

Reply: Probably yes. However, 2010 total anthropogenic CO emissions range from 15 to 27 Tg/yr for Western and from 6 to 12 Tg/yr for Central Europe (Granier et al. 2011), so uncertainties are of comparable magnitude, even though probably smaller. The statement has been amended accordingly.

7) What about surface ozone impacts, which depend on the wildfire-anthropogenic emissions interactions?

Reply: We have added a paragraph to the end of Section 3.4:

"We also estimate that for Europe, ozone (O_3) produced from wildfires emissions, a secondary air pollutant (Miranda et al. 2008, Jaffe and Widger 2012), are and will remain below levels that make them 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 Figure 2 and a similar residence time than for PM2.5 (Jaffe and Widger 2012), we estimate a wildfire contribution to the O_3 average concentration for Portugal in August of 0.4 μg / m^3, one fifth of the corresponding value for PM2.5, while the WHO 8-hour limit of 100 µg / m³ is four times higher than the 24-hour WHO limit for PM2.5 (25 µg / m³). "

8) Page 15, Line 355. Missing reference year. Page 18, Line 439 delete "more". Page 20, Line 473. delete "with". Page 21, Line 493. "implemented". Page 21, Line 514. delete "wildfires".

Reply: These have been corrected.

Other changes to the text

Correction of Lasslop et al. (2015) reference.

Updated Knorr et al. (2015, in review) to Knorr et al. (2016a).

Exchanged two last rows of Table 1 to keep the chronological order of publications.

Added references to Akagi et al. (2012), Ahlström et al. (2012), Jaffe and Wigder (2012).

Removed reference to Klimont et al. (in preparation) and substituted it by Stohl et al. (2015).

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Title:

Air quality impacts of European wildfire emissions in a changing climate

Authors:

Wolfgang Knorr 25/4/2016 22:26
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Wolfgang Knorr*[1], Frank Dentener[2], Stijn Hantson[3], Leiwen Jian[4, 5], Zbigniew Klimont[6] & Almut Arneth[3]

[1]Physical Geography and Ecosystem Analysis, Lund University, Sölvegatan 12, 22362 Lund, Sweden

[2] European Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy.

[3] Karlsruhe Institute of Technology, Institute of Meteorology and Climate research, Atmospheric Environmental Research, 82467 Garmisch-Partenkirchen, Germany.

[4] Asian Demographic Research Institute, Shanghai University

[5] National Center for Atmospheric Research, Boulder, Colorado, USA

[6] International Institute for Applied Systems Analysis, Laxenburg, Austria

*Corresponding author's email: wolfgang.knorr@nateko.lu.se

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 the 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 summarize the importance of wildfires on air quality in Europe (Section 1.1), then review what is known about the influence of past climate change on European wildfires (Section 1.2) and existing efforts to models change in future wildfire emission (Section 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) in order to identify potential geographical hot-spots 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 potentially 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 air-borne 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; EMEP Assessment Report, in preparation; 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).

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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 south-western 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 extra-tropical 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 emissions inventories, for example organic carbon, 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 one to two 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 as been warming by 0.1°C per decade, a trend that is significant at the 95% level. A 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 by between 0.3 and 0.5 mm per decade for southern Europe and 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

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Wolfgang Knorr 26/4/2016 15:20
Deleted: The aim of the present contribution is twofold: First to review published evidence and assess whether past changes in European climate have led to an increase in air pollutant emissions from wildfires, and second, to combine inventories, scenarios and model-based future projections of anthropogenic and wildfire emissions with climate, terrestrial-ecosystem and fire model simulations in order to identify potential geographical hot spots where certain pollutants from wildfires might reach or exceed anthropogenic emission levels as a first indication of where potentially health related risks may be caused by climate change induced forest fires.

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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, and thus making them more flammable. The Western U.S. 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 U.S., 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 where 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 U.S., 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 Fernandez-Muñoz (2012) in a study for 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 abondanment as a possible cause.

High-quality quantitative data on fire occurrence Europe-wide, recompiled in the European Forest Fire Information System (EFFIS), is only available starting from the 1980´s. 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

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in fire management and prevention after the big fires of the 1970´s and 80´s (Turco et al., 2016). Of the other EU countries, only Croatia has comparable levels of burned area per year as the southern European countries already referred to (i.e. above 20,000 ha/year 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 the 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), which however only reports 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 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).

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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 a key role. 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

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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, as for example 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 or socio-economic, or both in combination.

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, but mainly a climate driven increase

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when using SPITFIRE, 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, and 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 of 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 re-scale 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 burned area for Europe against 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.

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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 RCP 4.5 (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 against 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).

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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 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 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 direction and 1° in longitudinal direction at the equator, increasing in degrees longitude 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 (Klein-Goldewijk et al. 2010). Future population scenarios are from the Shared Socio-Economic Pathways (SSPs, Jiang 2014), using SSP5 (a conventional development scenarios 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, as compared to high population growth and slow urbanisation for developing regions). Gridded population distributions beyond 2005 are produced by separate re-scaling of the urban and rural populations from HYDE of 2005 (see Knorr et al. 2016a for details).

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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), available from http://www.falw.vu/~gwerf/GFED/GFED4/. 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 (PM2.5) and SO_2. In order to avoid as much as possible the inclusion of agricultural burning erroneously classified as wildfires, we only use the months May to October from the climatology.

For anthropogenic emissions of air pollutants, we use the GAINS model (Amann et al., 2011) estimates developed within the ECLIPSE project (Stohl et al., 2015). Specifically, we use the GAINS version 4a global emissions fields (Kimont et al. 2013, Stohl et al. 2015, Granier et al. 2011), which are available for 2010 (base year), 2030 and 2050 at 0.5° by 0.5° resolution from the GAINS model website (www.iiasa.ac.at/web/home/research/researchPrograms/Global_emissions.html). 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

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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 PBL emissions (Braspenning-Radu et al., in review) because they do not include particulate matter, but instead 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 CLE anthropogenic emissions dataset 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 dataset (Braspenning-Radu et al., 2015, in review). Since this dataset does not provide PM2.5 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 Luxemburg as "Benelux", and the countries of former Yugoslavia plus Albania as "Yugoslavia &

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Albania", and 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 during 1997 to 2014, inclusive.

In the following, we compare anthropogenic and wildfire emissions of BC (black carbon), CO, NO_x, PM2.5 (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 Figure 1 shows, current anthropogenic

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emissions of CO, PM2.5 and BC are generally about two 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, PM2.5).

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 PM2.5 are the dominant pollutants emitted both by wildfires or human activities. The decline of total fire emissions towards dense population found in the GFED4.1s data (Figure 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, co-variation 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 Figure 1 is consistent with the model formulation of SIMFIRE. Furthermore, areas with fewer than 3 inhabitants / km^2 (see Appendix, Figure 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

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wildfires occurred in July and August 2010 (Kaiser et al. 2010) – 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 Figure 2b around 54°N, 39°E (Moscow can be located by high anthropogenic emissions slightly to the west), as do the fire in the western Peloponnese in 2007 (Boschetti et al. 2008). PM2.5 emissions of comparable magnitude are more widespread and are found again for Portugal and east of Moscow, but also along the western the coastal regions of 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 (Figure 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 (Figure 2f).

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Of the regions or countries analysed (Table 3), Portugal clearly stands out, representing not only around 27% of European wildfire emissions (here of PM2.5, 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%), Yugoslavia & Albania (9%), Spain (16%) and Greece (4% of European emissions), and these countries together contribute as much as 77% of total European PM2.5 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.

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3.2 Predicted changes in wildfire emissions

Simulated wildfire emissions of PM2.5 from Europe (Figure 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 Section 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

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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 highest emissions currently (Table 3), is estimated to retain its top position and experience a 23 to 42% increase in PM2.5 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, Yugoslavia & Albania and Greece have similar increases in emissions to Portugal, all but Spain and France showing 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 significantly 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).

Results of the sensitivity study using the alternative SIMFIRE parameterisation are shown in the Appendix (Figure A3, Table A1). For all European regions, LPJ-GUESS-SIMFIRE simulates ca. 30% lower burned area compared to the standard

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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 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 PM2.5 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 (Figure 1), which largely follows the relationship for anthropogenic emissions but with a more than two orders smaller magnitude, 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, combining high RCP8.5 climate and CO_2 change with SSP3 rapid population decline over large parts of Europe (Figure 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, Figure A4; this case would require that most greenhouse gas emissions leading to RCP8.5 would have to originate outside of Europe).

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Monthly wildfire CO and PM2.5 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 (Figure 4). In this case, we combine both RCP4.5 (Figure 4a) and RCP8.5 (Figure 4b) with the SSP5 scenario (fast urbanisation and high population growth, or slow decline in eastern Europe), so that

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differences in simulated wildfire emissions between the two sub-figures 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 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 (Figure 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 Figure 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 PM2.5, wildfire emissions may reach around 10% of the anthropogenic counterpart for less than 10 inhabitants / km^2. Even for MFR (Figure 4b), CO from wildfires remain a minor source, but for BC and PM2.5 (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 have already now comparatively high emissions (Figure 2). A spatially explicit analysis of future emissions using again RCP8.5, SSP5 population and MFR anthropogenic emissions, reveals that by 2090 wildfires could become the dominant source of BC for much of

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Moved down [2]: The importance of wildfire emissions will further increase with under stronger climate change, but the main reason is 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.

Portugal (Figure 5a). For PM2.5 in Portugal or BC and PM2.5 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 (Figure 5b), in 2030 fire emissions are dominating for most of Portugal, coastal regions of former Yugoslavia and Albania, western Greece plus some scattered parts of Spain, Italy and Bulgaria, and the northern part of eastern Europe (Russia, Ukraine, Belarus), 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 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 Figure 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 feedbacks 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 polution 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.

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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

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similar relative magnitude, even though likely somewhat smaller than for wildfire emission (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 therefore remains whether the magnitude can also reach levels sufficiently high to interfere with air quality policy aimed at limiting anthropogenic sources. To illustrate this, we focus on the most relevant air pollutant component, PM2.5. In the following, we derive an approximate threshold for peak-month wildfire PM2.5 emissions ($E_{PM2.5}^{p.m.}$) above which these might interfere with air quality goals. According to Figure 2e, the highest emissions in central and northern Portugal are around 0.05g/m^2 during the peak month. Assuming that the peak month contributes about half the annual wildfire emissions (Figure 2f), a boundary layer height h=1000 m (as a compromise between night and day time) and a life time of the emissions of τ=1/50 yr (7.3 days), and that the impact on mean annual mean (not peak-month) PM2.5 concentrations corresponds roughly to the steady state concentrations, $C_{PM2.5}$, with $E_{PM2.5}^{p.m.}$=0.05 g/(m^2 month), we obtain:

$$
\begin{aligned}
\mathrm{C}_{\mathrm{PM2.5}} &= E_{\mathrm{PM2.5}}^{\mathrm{p.m.}} * 2\ \mathrm{months/year} * \tau / h \\
&= 0.05 * 40\ \mu\mathrm{g} / \mathrm{m}^3 \\
&= 2\ \mu\mathrm{g} / \mathrm{m}^3. \qquad (1)
\end{aligned}
$$

During the peak fire month, this would amount to six times this level, i.e. 12 µg / m^3 (half of the amount emitted in 1/12 of the time). For 2012, most air quality stations in central to north Portugal report mean annual PM2.5 values of up to 10 µg / 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 (Equation 1), i.e. 0.8* $\mathrm{C}_{\mathrm{PM2.5}}$ = 1.6 µg / 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.

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If the European Union in the future moved from its own air quality directive's target of 25 µg/m^3 annual average (EEA 2014) to the more stringent World Health Organization guideline of 10 µg/m^3 (WHO 2006), a contribution of 3 µg / 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 g/m^2 PM2.5 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 Figure 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, a secondary air pollutant (Miranda et al. 2008, Jaffe and Widger 2012), are and will remain below levels that make them 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 Figure 2 and a similar residence time than for PM2.5 (Jaffe and Widger 2012), we estimate a wildfire contribution to the O_3 average concentration for Portugal in August of 0.4 µg / m^3, one fifth of the corresponding value for PM2.5 (Equation 1). On the other hand, the WHO 8-hour limit of 100 µg / m^3 O_3 is four times higher than the 24-hour WHO limit for PM2.5 (25 µg / m^3).

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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. Partly this is 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 valid also 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 tripling or even quadrupling of emissions appear plausible, even if unlikely.
- The highest ratio of wildfire to anthropogenic emissions for CO, BC, and PM2.5 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 Mediterranean and north-eastern Europe, wildfires could become the main source of air pollution during the fire season, unless improved fire management systems would be 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.

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Author contributions: WK conceived of the study, carried out the analysis and wrote the first draft of the manuscript, FD contributed to conception of the paper, and to the scenario analysis. All authors contributed to discussions and writing.

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Tables

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 vegetation, empirical fire model no human impact	16 GCMs, 52 GCM-scenario combinations	Significant decrease in north-eastern, increase in western Europe, Italy and Greece, mixed results for Spain
Kloster et al. (2012)	carbon emissions	Globe	CLM process based model	MPI and CCM GCMs, SRES A1B, 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 North Africa	CLM 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, different CFWI codes and statistical models by country	Single RCM, SRES A2, 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, North Africa	CFWI meteorology only	6 GCM-RCM combinations 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, LPJ-SPITFIRE 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 population decline (SIMFIRE) or climate (SPITFIRE)
Knorr et al. (2016a)	carbon emissions	Globe	LPJ-GUESS-SIMFIRE process-based vegetation, 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;

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Table 2: Total anthropogenic emissions for European study area.

Data set	Description	Species	2010	2030	2050	2090
ECLIPSE CLE	Current legislation	CO	37,689	30,183	22,720	*16,970*
		PM2.5	2,712	2,370	2,031	*1,581*
		BC	465	399	224	*165*
		NO_x	9,581	7,929	4,207	*3,130*
		SO_2	10,680	7,380	3,697	*2,815*
PEGASOS BL-CLE	Baseline CLE, no change in emission factors after 2030	CO	32,011	18,870	17,573	8,479
		BC	525	153	99	29
		NO_x	8,253	3,775	2,936	2,596
		SO_2	10,533	3,419	3,150	2,837
ECLIPSE MFR	Maximum feasible reduction	CO		11,538	11,732	*5,866*
		PM2.5		567	552	*276*
		BC		55	50	*33*
		NO_x		1,519	1,478	*1,020*
		SO_2		1,560	1,443	*1,042*
PEGASOS MFR-KZN	MFR with GDP driven decline in emission factors towards 2100	CO	30,575	12,587	10,824	4,977
		BC	521	125	64	27
		NO_x	7,848	1,881	1,382	1,291
		SO_2	10,160	1,824	1,291	900
PEGASOS 450-MFR-KZN	MFR-KZN with 450 ppm atmospheric CO_2 stabilization target	CO	30,575	11,653	9,074	4,735
		BC	521	101	42	23
		NO_x	7,848	1,585	1,074	889
		SO_2	10,160	1,298	680	395

Emissions in Tg / yr; GDP: gross domestic product.
Number in italics: extrapolation by the authors.

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Table 3: Changes in simulated PM2.5 emissions for regions used in the analysis.

Country/region	GFED4.1s mean		Simulated emission changes 2010 to 2050 [%]						Simulated emission changes 2010 to 2090 [%]					
	1997-2014 emissions		RCP4.5 ensemble			RCP8.5 ensemble			RCP4.5 ensemble			RCP8.5 ensemble		
	[Gg/yr]	[g/(ha yr)]	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

Figures

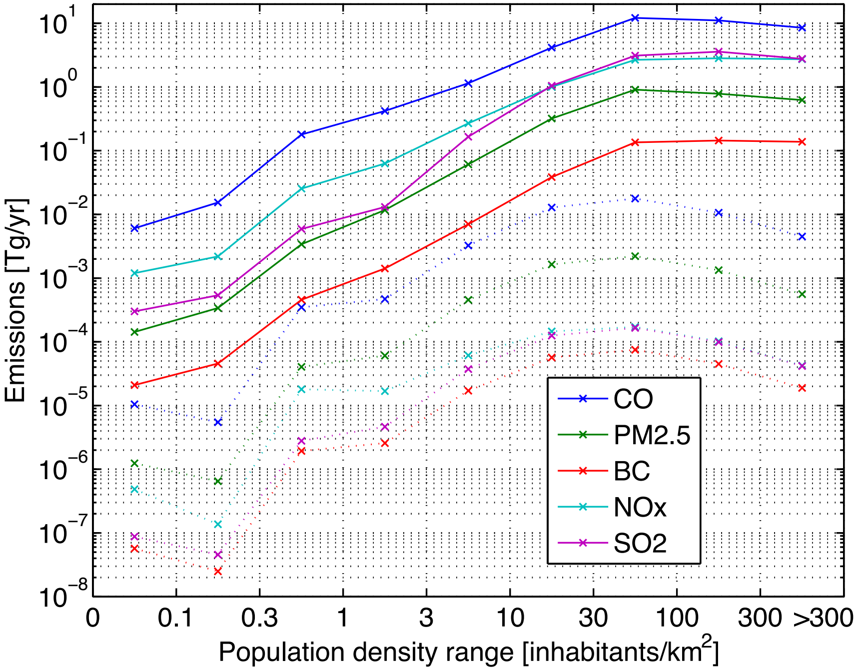

Figure 1: Current anthropogenic (solid lines) and wildfire emissions (dashed lines) for Europe by range of population density for various pollutants. Anthropogenic emissions are for 2010 and wildfire emissions average 1997-2014.

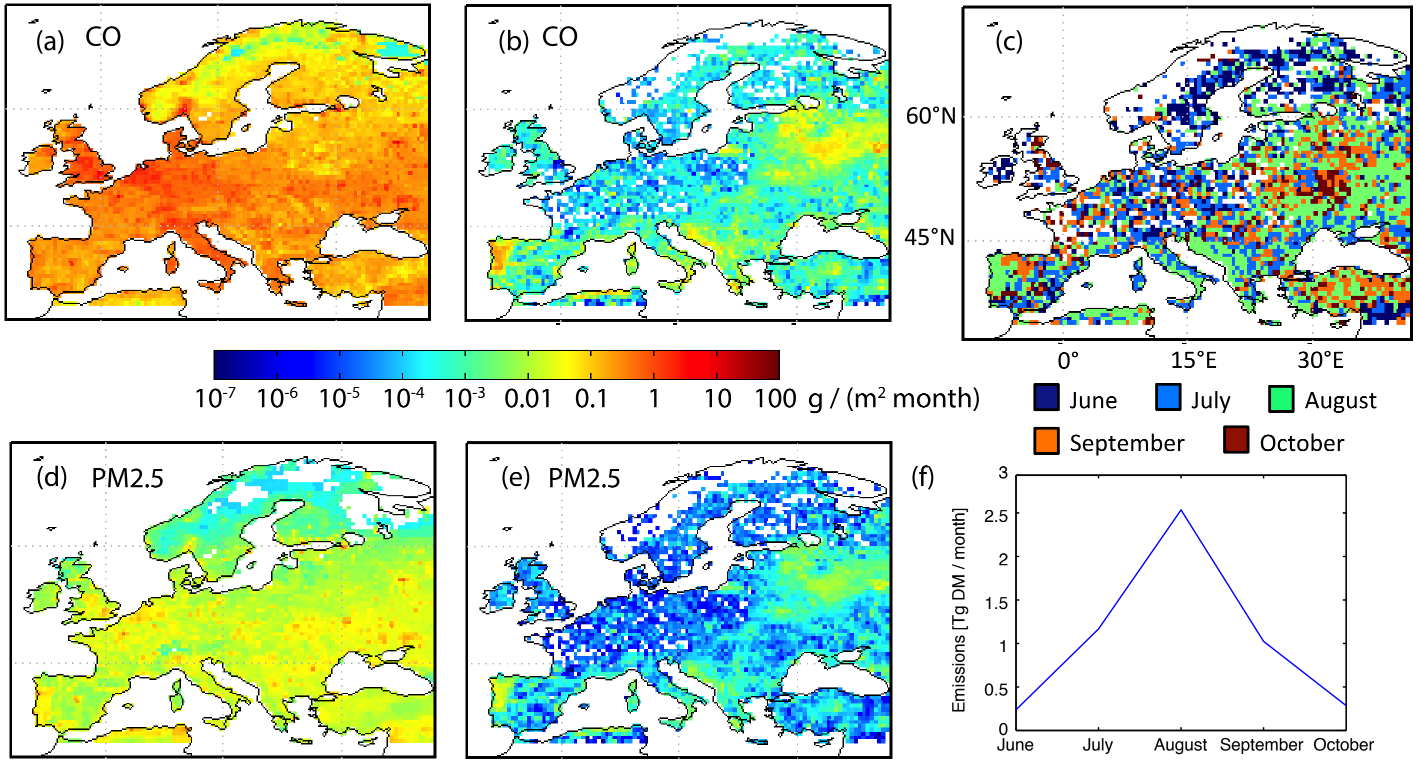

Figure 2: Emissions of CO (a, b) and PM2.5 (d, e) from anthropogenic sources (a, d) and wildfires (b, e) during peak month of fire season (c). (f) Total wildfire emissions climatology 1997-2014 in dry mass per month during the fire season for the European study. White: zero emissions.

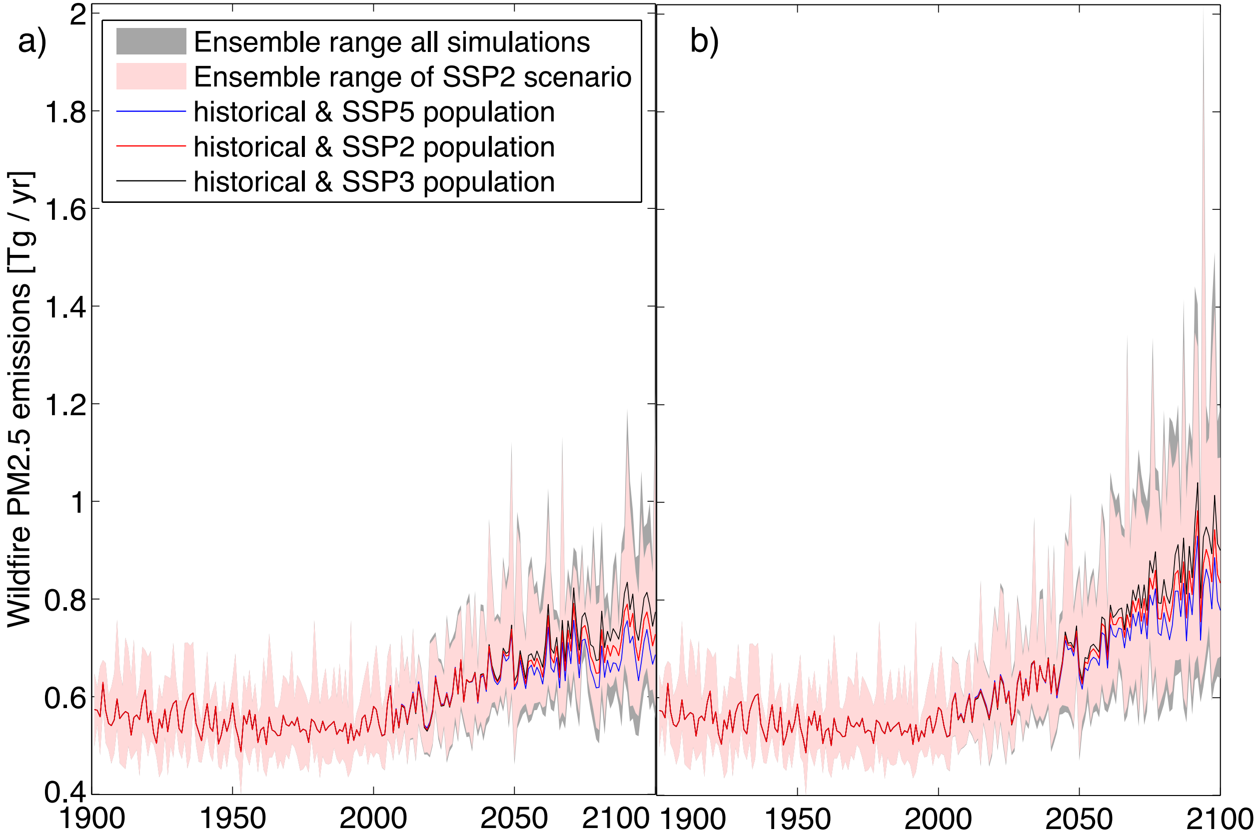

Figure 3: Ensemble means and ranges of simulated PM2.5 emissions for all European regions for RCP4.5 (a) and RCP8.5 (b). Historical population data is used for 1901 to 2005, different SSP population scenarios for the remaining period.

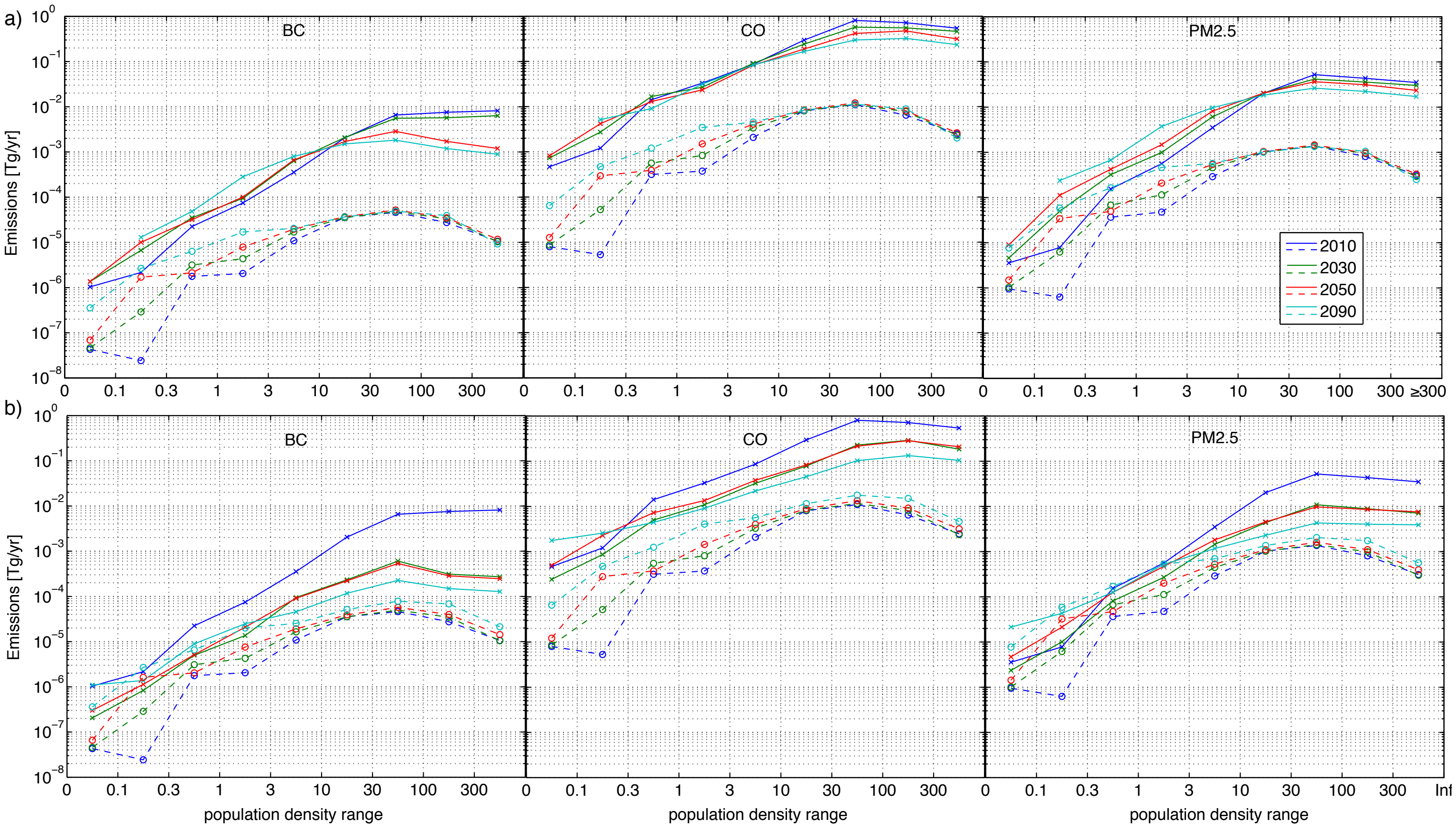

Figure 4: Monthly anthropogenic (solid lines, crosses) and wildfire emissions of selected pollutants (dashed lines, circles) for Europe during peak fire season by range of population density for different time windows and the SSP5 population scenario. a), RC4.5 with current legislation anthropogenic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

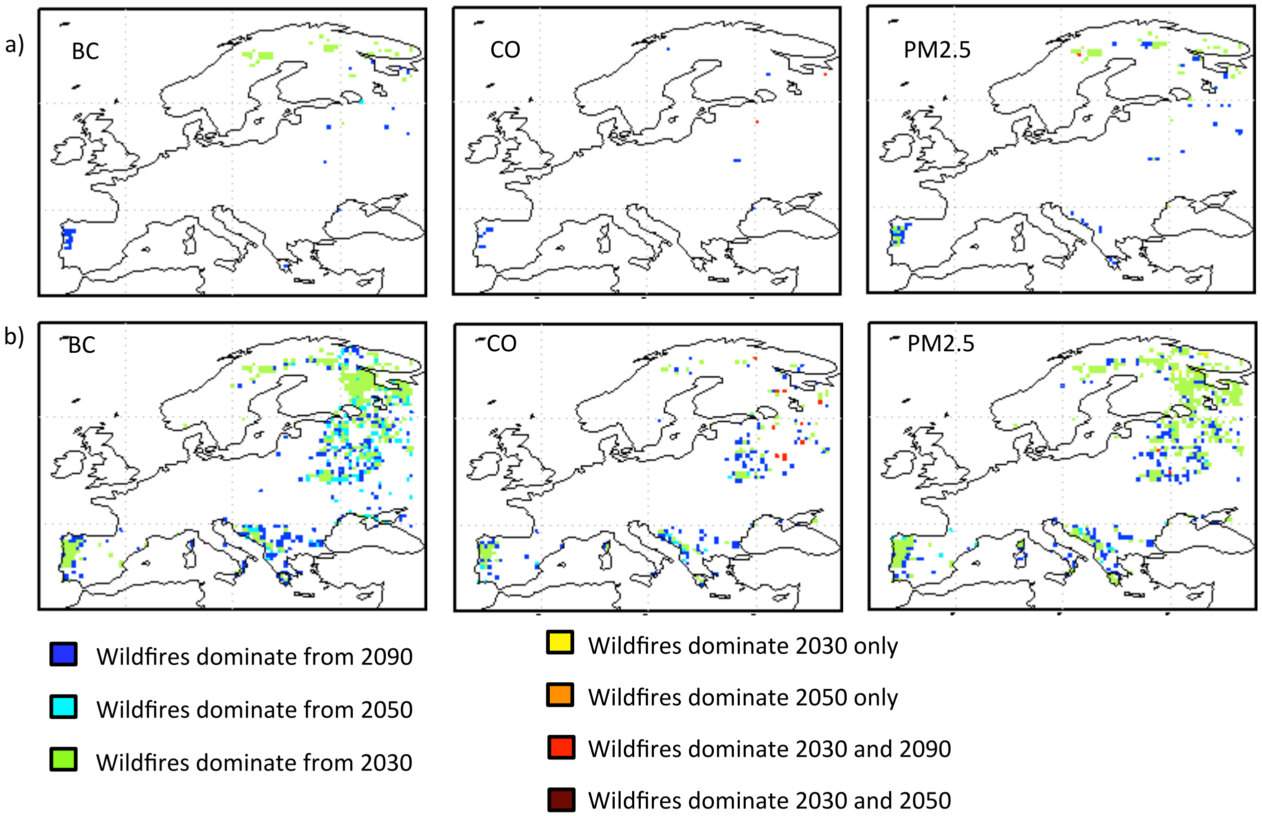

Figure 5: Areas where wildfire emissions exceed anthropogenic emissions in 2030, 2050 or 2090 on annual basis (a) or during peak fire season (b) (month of maximum wildfire emissions varying by grid cell), assuming RCP8.5 climate, SSP5 population and maximum feasible reduction anthropogenic emissions.

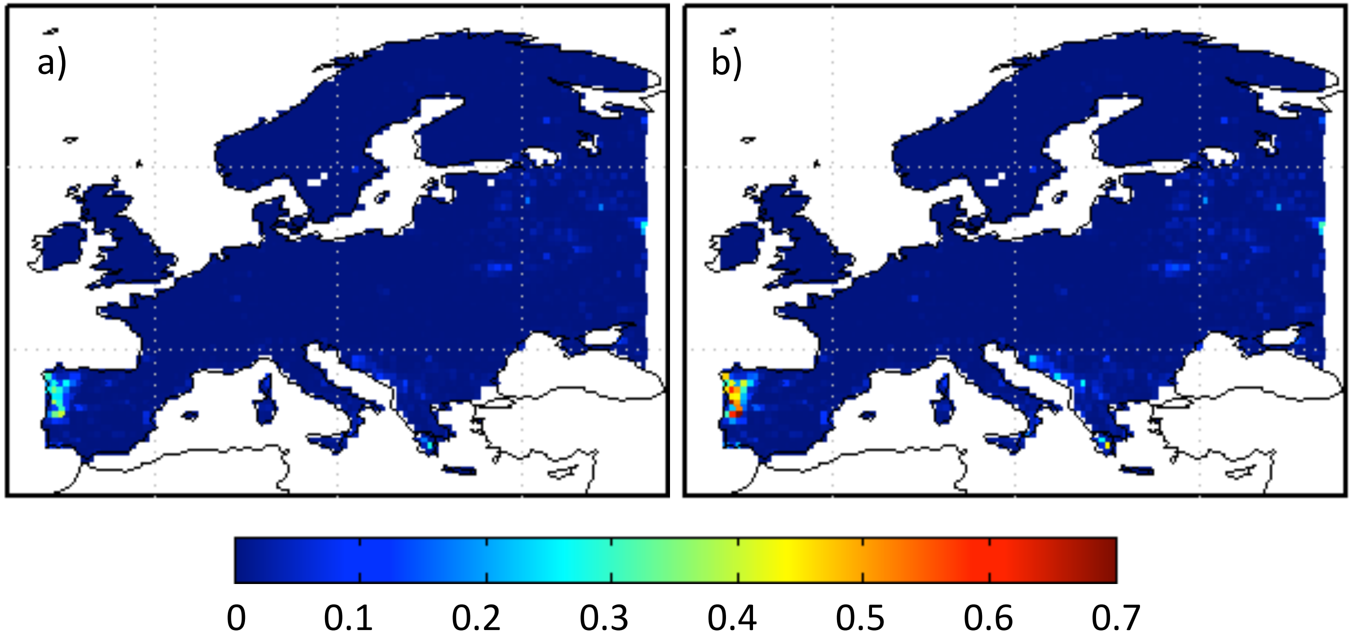

Figure 6: Wildfire PM2.5 emissions during peak fire season displayed on linear scale, in g / (m^2 month). a) current; b) 2090.

Appendix

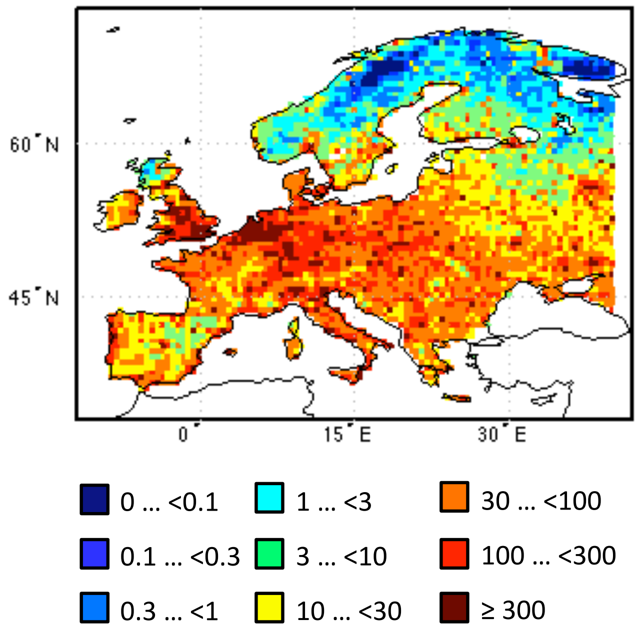

Figure A1: Current (2010) population density [inhabitants / km^2] in Europe by ranges considered in the analysis. Derived from gridded observed 2005 values extrapolated to 2010 using SSP2.

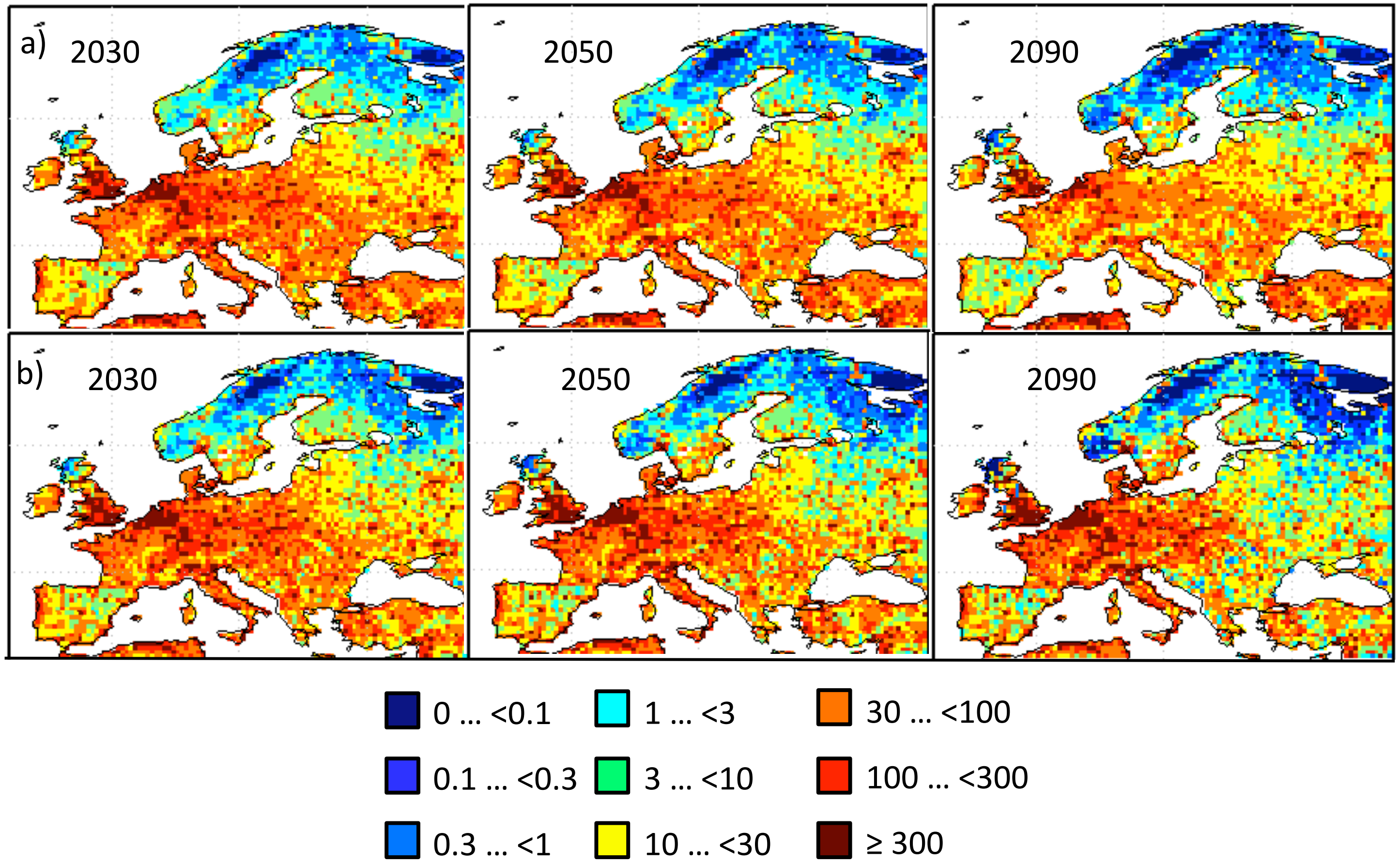

Figure A2: Projected population density [inhabitants / km^2] in Europe. a) SSP3; b) SSP5.

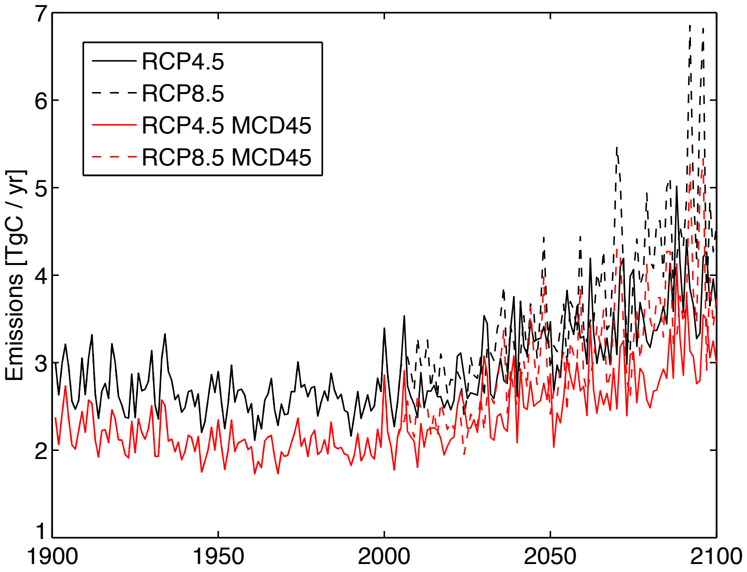

Figure A3: Wildfire carbon emissions for all European regions with the standard SIMFIRE parameterisation compared to runs using SIMFIRE optimised against MCD45 global burned area, for two RCP scenarios and simulations using the MPI global climate model.

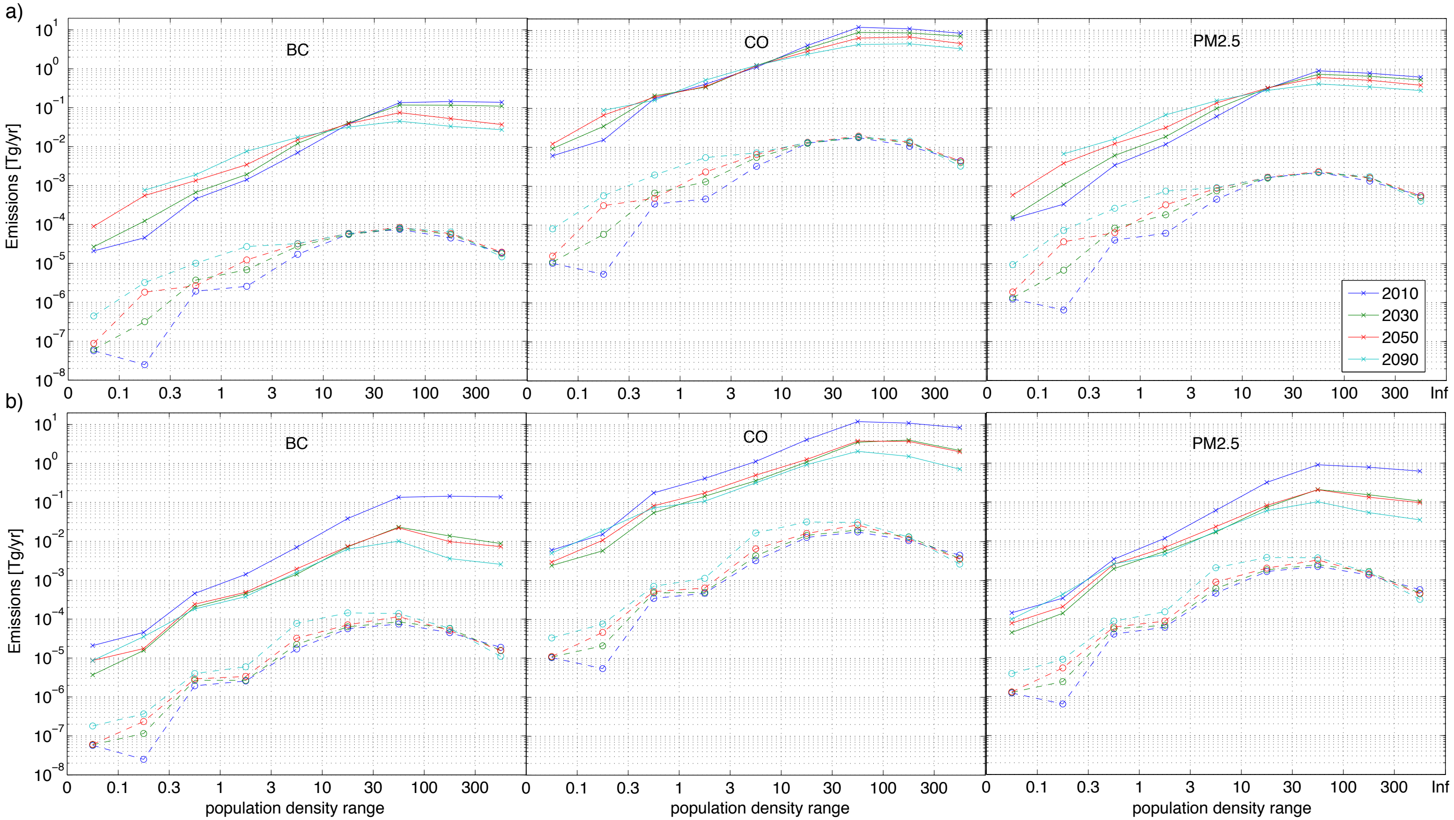

Figure A4: Annual anthropogenic (solid lines, crosses) and wildfire emissions (dashed lines, circles) for Europe by range of population density for selected pollutants and time windows. a) RCP4.5 climate, SSP5 population and current legislation (CLE) for anthropogenic emissions. b) RCP8.5 climate, SSP3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

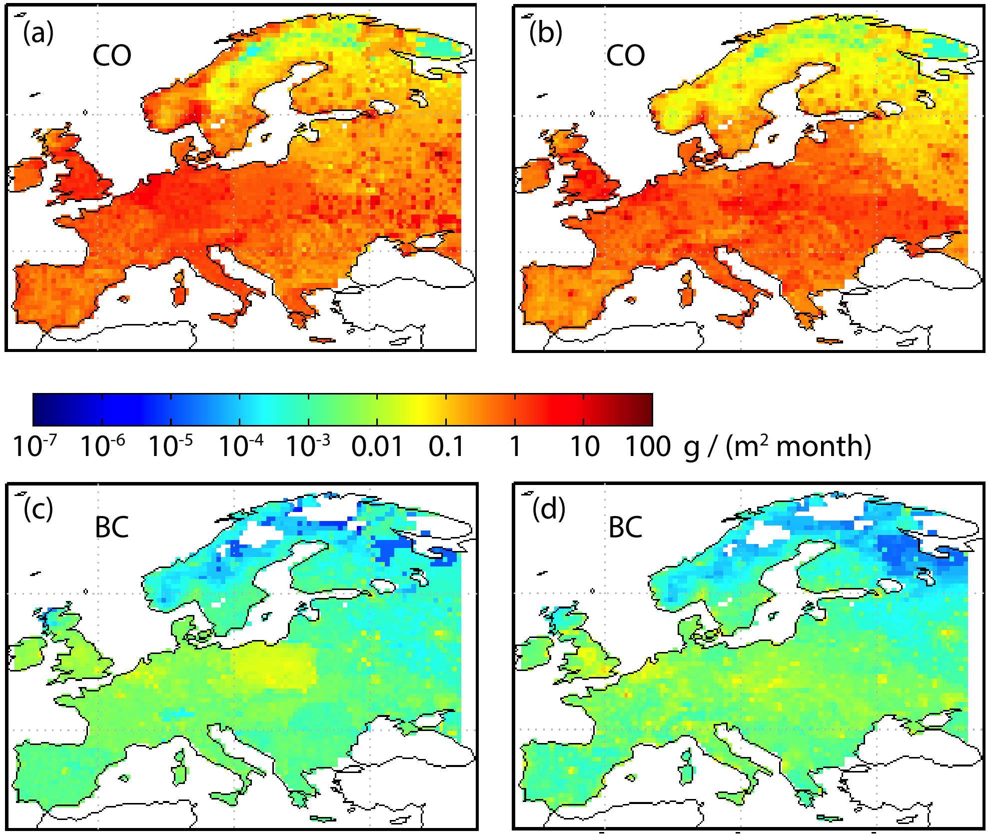

Figure A5: Comparison of annual anthropogenic CO and BC emissions for 2090, a, c) 50% of ECLIPSE GAINS 4a MFR for 2050 as assumed for 2090 in present study; b, d) PEGASOS PBL v2 MFR-KZN.

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Table A1: Sensitivity of predicted emissions 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.(1)	*MCD45*(2)	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*

(1) SIMFIRE standard parameterisation with MPI climate model output.

(2) SIMFIRE optimised against MCD45 global burned area product, also with MPI climate model output.

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For anthropogenic emissions of air pollutants, we use the GAINS model (Amann et al., 2011) estimates developed within the ECLIPSE project (Stohl et al., 2015). Specifically, we use the GAINS version 4a global emissions fields (Kimont et al. 2013, Klimont et al., in preparation, Granier et al. 2011), which are available for 2010 (base year), 2030 and 2050 at 0.5° by 0.5° resolution from the GAINS model website (www.iiasa.ac.at/web/home/research/researchPrograms/Global_emissions.html). The future emissions for 2030 and 2050 are available for two scenarios: 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 PBL emissions (Braspenning-Radu et al., in review) because they do not include particulate matter, but instead 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 CLE anthropogenic emissions dataset 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 dataset (Braspenning-Radu et al., 2015, in review). Since this dataset does not provide PM2.5 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).

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Klimont, Z., Höglund-Isaksson, L., Heyes, Ch., Rafaj, P., Schöpp, W., Cofala, J., Borken-Kleefeld, J., Purohit, P., Kupiainen, K., Winiwarter, W., Amann, M, Zhao, B., Wang, S.X., Bertok, I., Sander, R. Global scenarios of air pollutants and methane: 1990-2050. *In preparation.*

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Knorr et al. (2015)	carbon emissions	Globe	LPJ-GUESS-SIMFIRE process-based vegetation, 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