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Title:

Climate and demographic impacts on wildfire air pollution hazards during the 21st century

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Abstract:

Wildfires pose a significant risk to human livelihoods and are a substantial health hazard due to emissions of toxic smoke. It is widely believed that climate change, through increasing the frequency of hot weather conditions, will also lead to an increase in wildfire activity. More recently, however, new research has shown that trends in population growth and urbanisation can be as important for fire prediction as changes in climate and atmospheric CO_2, and that under certain scenarios, fire activity may continue to decline through most of the 21st century. The present study re-examines these results from the perspective of air pollution risk, focussing on emissions of airborne particulate matter (PM2.5). We combine an existing ensemble of simulations using a coupled fire-dynamic vegetation model with current observation-based estimates of wildfire emissions to predict future trends. Currently, wildfires PM2.5 emissions exceed those from anthropogenic sources in large parts of the world, while emissions from deforestation or peat fires constitute minor sources. We find that for Sub-Saharan Africa and southern China predictions of wildfire pollution risks depend almost entirely on population dynamics, whereas for North Australia and South America, it is mainly determined by climate change, with Southeast Asia lying somewhere in-between. Under a scenario of current legislation of anthropogenic emissions, global high population growth and slow urbanisation, wildfires may seize to be the dominant source in large parts of Sub-Saharan Africa. However, if anthropogenic emissions are strongly reduced, wildfires may both become the dominant source and lie above critical levels for health impacts in large parts of Australia, Africa, Latin America and Russia, and parts of southern China and southern Europe. This implies that controlling anthropogenic emissions will not suffice for attaining the World Health Organization air quality targets.

1 Introduction

Wildfires are a major natural hazard (Bowman et al. 2009) and an important source of air pollutants (Langmann 2009). Of these, emissions of fine aerosol particles, i.e. particulate matter up to a size of 2.5 microns (PM2.5), are of particular health concern, with no known safe levels of PM2.5 concentration in air, as noted by the World Health Organization (WHO 2005). While globally, most PM2.5 emissions come from human activities, wildfires can be an important source in large, more remote areas (Granier et al. 2011, van der Werf et al. 2010). There is an expectation that such emissions will become more important in the future (Kloster et al. 2010, Knorr et al. 2016a), because of a widely held view among both the general public and members of the research community that wildfire occurrence and severity have been increasing in recent decades, and will continue to increase due to climate change (Doerr and Santin 2016) and efforts to reduce anthropogenic emissions (EEA 2014).

Climate warming has already led to frequent hot and dry weather around the globe, increasing the probability of wildfires (Flannigan et al. 2012), and this is expected to continue into the future. Studies based on predicted fire severity indices from climate argue for large increases in burned area as a result of climate warming (Flannigan et al. 2005, Amatulli et al. 2013). However, a long-term increase in the length of the fire season or in weather conditions conducive of wildfires does not necessarily lead to increases in burned area (Doerr and Santin 2016). This is because at longer time scales, vegetation also responds to climate change, as well as directly to rising atmospheric CO_2 levels (Buitenwerf et al. 2012, Donohue et al. 2013). While CO_2 fertilization will lead to increased fuel load, enhancing emissions, it also leads to an increase in woody as opposed to herbaceous vegetation, with lower emissions due to decreased fire spread in shrublands (Kelley et al. 2014, Knorr et al. 2016b). Indeed, simulations with coupled fire-vegetation or statistical climate-envelope models generally show less increase in fire activity until 2100 when accounting not only for climate, but also for these vegetation factors (Krwachuk et al. 2009, Kloster et al. 2010, Knorr et al. 2016c).

Another factor that has so far received less attention are changes in human population density. Contrary to common perception, higher population density tends to be associated with lower burned area (Archibald et al. 2009, 2010, Lehsten et al. 2010, Knorr et al. 2014, Bistinas et al. 2014), even though more humans tend to lead to more, but smaller fires (Archibald et al. 2009, 2010). This can be explained by the concept of the ignition-saturated fire regime, which is reached at very low levels of population density. Above this level, human impact is less manifested as enhancing

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burned area by providing ignitions, but more by creating barriers to and suppressing fire spread, thus reducing area burned (Guyette et al. 2002). Indeed, coupled vegetation-fire models that include human effects suggest a reduced rate of increase of fire activity during the 21st century compared to simulations not accounting for demographic changes (Kloster et al. 2010), or even a decline in burned area (Knorr et al. 2016c) or emissions (Knorr et al. 2016b) for moderate levels of climate change combined with slow urbanisation and fast population growth. It was found that differences between demographic scenarios can be more important than differences between climate scenarios or climate models. There is also observational evidence for a long-term declining trend in past fire activity or emissions from wildfires (Marlon et al. 2008, Wang et al. 2010, van der Werf et al. 2013), and more recent negative trends in Africa have been related to the expansion of cropland, that is itself a result of increasing population density (Andela and van der Werf 2014).

The question is therefore not only how climate and vegetation change in the future will impact on wildfire hazards, but also what the role of total population growth and changes in spatial population distribution is for those predictions. Following a similar study for Europe (Knorr et al. 2016a), we will use PM2.5 emissions from wildfires as an example fire hazard to illustrate the relative effects of climate, vegetation and demographics, and base our projections on observation-based wildfire emissions, using vegetation-fire model simulations to project relative changes. The results are meant to be indicative of the importance of demographic and climatic changes for the expected future development of wildfire hazards. All this, however, needs to be seen against a background of considerable uncertainties surrounding future projections of wildfire emissions (Knorr et al. 2016a, Doerr and Santin 2016).

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2 Methods

2.1 Models and driving data

We use the LPJ-GUESS global dynamic vegetation model (Smith et al. 2001, Ahlström et al. 2012) coupled to the global semi-empirical fire model SIMFIRE (Knorr et al. 2014). A detailed description of the coupling between SIMFIRE and LPJ-GUESS and of methods used to compute wildfire emissions in terms of biomass can be found in Knorr et al. (2016b). LPJ-GUESS is a patch-scale dynamic vegetation model that represents age cohorts and computes vegetation establishment and growth, allocation of carbon pools in living plants, and turnover of carbon in plant litter and soils. SIMFIRE provides burned area to LPJ-GUESS on an annual basis, which then evokes plant mortality according to a plant-functional-type (PFT) dependent probability. Specified fractions of plant litter and live leaf biomass are burnt and emitted into the air in a fire, while the remaining biomass of the killed vegetation is transferred to the litter pool (see Knorr et al. 2012). Population data needed to drive SIMFIRE are based on gridded data from HYDE 3.1 (Klein-Goldewijk et al. 2010) up to 2005, and then re-scaled using per-country relative growth in population and urbanisation rates, retaining the urban masks of the HYDE data. Grid cells with more than 50% past or future cropland area (in either the RCP6.0 or 4.5 land use scenarios of Hurtt et al. 2011) were also excluded (see Knorr et al. 2016b, c for details).

In order to compute emissions of chemical species, we use the emission factors of the Global Fire Emissions Database version 4 (GFED 4, Van der Werf et al. 2010, based mainly on Akagi et al. 2011, see http://www.falw.vu/~gwerf/GFED/GFED4), which are fixed ratios between emission rates of various pollutant species and rates of combustion of dry biomass differentiated between fires in (1) savannas and grasslands, (2) tropical, (3) boreal and (4) temperate forests. We assign a grid cell to

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(1) if the dominant PFT (the one with the largest leaf area index at full leaf development) is a grass, to (2) if it is a tropical, to (3) a boreal and to (4) a temperate woody plant (see Knorr et al. 2012 for list of PFTs).

2.2 Simulations and scenarios

Simulations are driven by output from an ensemble of eight global climate models from the Climate Model Intercomparison Project 5 (CMIP5, Taylor et al. 2012) for two RCP (Representative Concentration Pathway, van Vuuren et al. 2011) climate scenarios: 4.5 (moderate) and 8.5 (high degree of climate change). Simulations for 1901 to 2100 are carried out on a global equal-area grid with one by one degree spatial resolution at the equator, but constant east-west spacing of the grid cells when moving towards the poles in order to keep the grid cell area constant (Knorr et al. 2016b).

Population projections follow the Shared Socioeconomic Pathways (SSPs, Jiang 2014). The SSPs are based on qualitative narratives following five different development pathways which have been translated into quantitative projections of a range of socio-economic and biophysical factors. Globally, SSP2 reflects an intermediate case (medium population and economic growth and a central urbanisation case), SSP3 high population growth and slow urbanisation with slow economic development, and SSP5 rapid but fossil-fuel driven economic growth with slow population growth and fast urbanisation. However, there are regional variations in demographic trends under each SSP. In contrast to developing countries and the world as a whole, high-income countries have low population growth for SSP3 but high population growth for SSP5. We did not consider the SSP1 scenario because its sustainability assumptions lead to low emissions and the scenario is therefore not compatible with the RCP8.5 climate scenario, nor did we use SSP4, since it is similar

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to SSP2 in its population projections. The matrix of three SSPs and two RCP scenarios represents a wide range of future climate and socio-economic conditions.

In addition to the emission fields simulated by LPJ-GUESS-SIMFIRE, we also use the GFED4.1s observation-based emissions fields for wildfires (van der Werf et al. 2010, updated using Randerson et al. 2012 and Giglio et al. 2013) aggregated to 0.5 by 0.5 degrees resolution and then re-scaled in time by country or groups of countries in some cases (following the methodology of Knorr et al. 2016a). For larger countries, scaling is done by sub-national regions, which were chosen in such a way as to isolate major fire areas found in GFED4.1s. For a list of regions/countries, see Table A1 in the Appendix. The use of countries accounts for the high degree of policy or cultural impact on fire regime (Bowman et al. 2011). In order to account for demographic effects at the grid-cell scale, we combine a scalar accounting for climate and vegetation effects, f_{cv}, which is uniform in space across each region, with a scalar accounting for demographic effects, f_p, which is applied at each grid cell separately:

$$E(x,t) = f_{cv}(R(x),t) * f_p(p(x,t)) * E_{GFED}(x) \qquad (1)$$

with E the re-scaled emissions, x the geographic location on the 0.5 by 0.5 degree grid used for the analysis, t time, R the region/country found at location x, E_{GFED} the annual emissions climatology from GFED 4.1s (average for 1997 to 2014). The population effect, f_p , is equal to the population multiplier of SIMFIRE (Knorr et al. 2016b):

$$f_p(p) = \exp(-0.0168*p'(p)). \qquad (2)$$

p' here is the minimum of population density p and 100 inhabitants per km^2, i.e. the function is constant for values of p above 100 inhabitants per km^2 (Fig. A1). We have introduced this cap, which is only used for scaling observation-based inventories by LPJ-GUESS-SIMFIRE output but not by SIMFIRE itself, in order to prevent large

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relative increases in emissions during the scaling procedure, when population density decreases from high values. We thus consider areas with higher population density than 100 per km^2 to be essentially wildfire free. The combined climate and vegetation effect is defined as

$$f_{cv}(R,t) = \Sigma_R\, E(x',t) \,/\, [\Sigma_R\, E(x',t_0) * \Sigma_R\, f_p(p(x',t))]. \qquad (3)$$

Here, the sums are over all grid cells x' of the LPJ-GUESS 1-degree equal-area grid that belong to region/country R. For countries where 90% or more of the grid cells of the LPJ-GUESS grid have been excluded because they have a current or future cropland fractions of 50% or higher (highly agricultural regions: Moldavia and Bangladesh), or for which LPJ-GUESS simulates zero current emissions in at least one simulation (Greenland), we set $f_{cv}(R,t)$ =1. Gridded population data is based on HYDE 3.1 (Klein-Goldewijk et al. 2010), and future population patterns are re-scaled from 2005 population data using per-country population increases and changes in urbanization level, retaining the urban masks of the HYDE data (see Knorr et al. 2016c for details).

2.3 Analytical Framework

In our analysis, we focus on four time windows: current, 2030, 2050 and 2090. For current, we use 2010 population fields and annual anthropogenic emission data, as well as the mean annual emissions of GFED4.1s, which span the period 1997-2014. For the future time windows, we again use population fields and anthropogenic emissions from that year, but average emissions simulated by LPJ-GUESS-SIMFIRE spanning a period of 21 years centered on each of these years (i.e. 2020 to 2040 for the 2030 time window, etc.). While LPJ-GUESS-SIMFIRE simulations are carried out on a 1-degree equal-area grid, all spatially explicit analysis is carried out on a global 0.5 by 0.5 degree grid.

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To assess the relevance of PM2.5 emission rates, we both compare them to those from anthropogenic sources, and consider an approximate threshold above which they can be considered relevant for human health and air quality policy. The World Health Organization has adopted an air quality policy target of 10 μg/m^3 on an annual average, pointing out that there is no established safe upper limit and that the target was set considering background concentrations of 3–5 μg m^{-3} in North America and Western Europe. We follow here Knorr et al. (2016a) and assume a typical boundary height of 1000 m and a life time of 1/50 years (about 7 days). Pollutants from wildfires are inject into the atmosphere from large plumes, which have a global average height of around 1400 m, but only about 4–5% of wildfire emissions are emitted into the free troposphere, the rest into the boundary layer (Veira et al. 2015). Here, we assume that after about one week, most of PM2.5 is either deposited or effectively mixed into the free troposphere. We also neglect horizontal transport between 0.5 by 0.5 degree grid cells and compute an annual budget based on annual mean emissions and pollutant life time. Using these idealized conditions, which are meant as a first guidance, we arrive at a threshold of 0.5 g m^{-2} yr^{-1} for PM2.5 emissions corresponding to a mean annual concentration of 10 μg m^{-3}. In this analysis, we use 0.2, 0.5 and 1 g m^{-2} yr^{-1} as alternative thresholds spanning a critical range for health and air-quality policy purposes.

For anthropogenic emissions, we use the GAINS 4a data (Amann et al., 2011) developed as part of the ECLIPSE project (Granier et al. 2011, Klimont et al. 2013, Stohl et al., 2015) for the years 2010 (for current conditions), 2030 and 2050. There are two future scenarios: current legislation (CLE), and maximum feasible reductions (MFR). MFR corresponds to a policy driven abatement scenario with the aim, among others, to lower PM2.5 emissions to a level to minimize health impacts (Amann et al.

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2011). Following Knorr et al. (2016a), we estimate 2090 CLE emissions assuming constant *per capita* emissions after 2050 but changing population according to the SSP3 scenario. For MFR, 2090 emissions are assumed half of the corresponding 2050 levels. As the CLE and MFR scenarios do not account for CO_2 emissions, both are in principal compatible with the CO_2 equivalent greenhouse gas emissions of both RCP scenarios, even though the non-CO_2 greenhouse gas emissions may differ.

For a regional analysis, we use a global map of nine major world regions to facilitate a global-scale analysis of our results (see Fig. A2). Of these, three belong to the high-income group of countries of the SSP scenarios (see Jiang and O'Neill 2015): High-income Europe, Australia & New Zealand, and North America. Countries of Europe belonging to the middle-incoming group were assigned Eastern Europe and Central Asia, which also includes Russia. Countries of the Middle East (Israel, oil-rich states of the Persian Golf) or East Asia (Japan, South Korea) belonging to the high-income group were excluded, which only account for a very small fraction of wildfire emissions in their respective group.

3 Results

3.1 Current patterns of wildfire pollutant emissions

The analysis presented in this sub-section concerns exclusively observation-based emission inventories. Currently 14 million km^2 of land area are affected by wildfire PM2.5 emissions that exceed 0.5 g m^{-2} yr^{-1}, used as an indicative threshold for serious health impacts, mainly in Sub-Saharan Africa, North America, South Australia, Southeast Asia, and the boreal zone (numbers are for the 0.5 by 0.5 degree grid: 23 million km^2 for a threshold of 0.2 and 8 million km^2 for a threshold of 1 g m^{-2} yr^{-1}) According to the GFED4.1s and ECLIPSE inventories (Fig. 1), PM2.5 emissions over large parts of the globe are dominated by wildfires, in particular the boreal zone and

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the semi-arid tropics. Even in the humid tropics, such as the Amazon basin or Southeast Asia, wildfires are prevalent and deforestation fires still play a comparatively minor role. Only Indonesia is clearly dominated by deforestation and peat fire emissions. Of the nine world regions, four (Sub-Saharan Africa, Latin America & Caribbean, Eastern Europe-Russia-Central Asia and Australia & New Zealand) have higher wildfire than anthropogenic emissions of PM2.5 on an annual basis (Table 1).

There are large, remote areas where, despite low emission rates, wildfires are the highest emissions source because anthropogenic emissions are even lower. This applies for example to large parts of the boreal zone, central parts of Australia, much of the western US, or the northern part of the Amazon. However, large regions also have emissions above the upper critical range from 0.5 to 1 g m^{-2} yr^{-1}, mainly in the boreal-forest areas (Alaska, Canada, Russia), the semi-arid tropics (the African savannas, the areas south of the Amazon basin, Southeast Asia from Myanmar to Cambodia and Northern Australia), and southeastern Australia in the temperate zone.

Other pollutants show a similar pattern of dominance (Fig. 2), but with some important differences: for CO and NO_x, anthropogenic sources are more important, and only Sub-Saharan Africa and Australia & New Zealand have emissions of these gases from wildfires close to or surpassing those from anthropogenic sources (Table 1). For NO_x, deforestation fires in the Amazon are also of minor importance compared to wildfires (Fig. 2b). For BC, Sub-Saharan Africa has very high but Australia & New Zealand very low anthropogenic sources, which is reflected in the dominance pattern shown in Fig. 2c. BC from wildfires is also important in temperate North America and central Asia.

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A breakdown of PM2.5 emission patterns by population density is shown in Fig. 3. It shows current emissions per area averaged over all grid cells of a given region that fall into a certain population-density range. Fig. 3 reveals the expected trend of increasing anthropogenic emissions where more people live. By contrast, for Sub-Saharan Africa, Latin America & Caribbean, Eastern Europe-Russia-Central Asia and South & Southeast Asia, wildfires show peak values with maximum emissions in regions of intermediate population density: Sub-Saharan Africa and Latin America & Caribbean at 1 to 10, Eastern Europe-Russia-Central Asia at 0.1 to 1, and South & Southeast Asia at 10 to 100 people km^{-2}. Deforestation fires are of minor importance for air pollutant emissions, except for Latin America & Caribbean, where they occur mainly in sparsely populated area, and for South & Southeast Asia, where they are as important as wildfires and most significant in areas of high population density. It is important to note that within South & Southeast Asia (Fig. A2), wildfires occur mainly in South-East Asia proper, but deforestation fires in Indonesia (Fig. 1a). Indonesia is also the only region where emissions from peat fires are relatively important for air pollution. In High-Income Europe and Developing Middle East & North Africa, wildfires show a similar increase with population density as anthropogenic emissions with the consequence that they are much smaller than anthropogenic emissions in all areas (for Developing Middle East & North Africa their magnitude is also very low *per se*). For North America, wildfires have the reverse trend compared to anthropogenic emissions, and for Australia & New Zealand and Developing East Asia, wildfire emissions happen at a similar average rate across all population density categories. These different trends between wildfires and anthropogenic sources lead to a situation where the former become the dominant source below a certain value of population density, which is 10 for Australia & New

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Zealand, and 1 inhabitant per km^2 for the other world regions. Developing East Asia also has the highest per-area anthropogenic emissions, which makes wildfire emissions appear to be generally of minor importance compared to current anthropogenic-emission levels.

3.2 Simulated changes in emissions

In this sub-section we present results from simulation with LPJ-GUESS-SIMFIRE. These differ from those presented in the following sub-sections, where the relative temporal changes from the LPJ-GUESS-SIMFIRE simulations are used to scale current observed emissions (Equ. 1). The ensemble mean PM2.5 emission shows a continuous declining trend for Sub-Saharan Africa across both the 20th and the 21st centuries for the moderate climate change scenario (RCP4.5, Fig. 4). Only the two ensembles with fast urbanisation show a slight increasing trend starting after 2050 for the medium population projection (SSP2 with fast urbanisation), or around 2030 for the low population growth scenario (SSP5). The range of predictions across climate models is about as large as the range of predictions across demographic scenarios. The result is surprisingly similar for the high climate change scenario (RCP8.5), where the central SSP2 demographic scenario still shows no clear increase in emissions even towards the end of the 21st century (Fig. 5). For Sub-Saharan Africa, demographic trends are by far the dominant driver of changes in fire regime, while differences between climate scenarios are minor. For the two scenarios with fast urbanisation (with either SSP2 or SSP5 population trends), this region shows a continuing decline in PM2.5 emissions from wildfires. The effect of changing only the urbanisation scenario on emissions is approximately half compared to changing both the urbanisation and population scenarios (i.e. changing SSP2 to SSP2 with fast urbanisation vs. changing SSP2 to SSP5; or changing SSP2 to SSP2 with slow

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urbanisation vs. changing SSP2 to SSP3). This region clearly stands out not only because it has by far the largest share of global wildfire pollutant emissions (Table 1), but also because of its large decline in fire activity driven by population trends.

The other two tropical regions, Latin America & Caribbean and South & Southeast Asia, differ from Sub-Saharan Africa in that the simulated historical decline is less steep, and that the future scenarios show an upward trend that is only slight for RCP4.5, but steep for RCP8.5. The range of predictions for only the central SSP2 scenario (ensemble ranges for the medium population and central urbanisation scenario, dark grey area in Fig. 4 and 5) is almost as large as that for the entire ensemble, indicating a reduced role for demographic change, with climate change as the main driver. For Latin America & Caribbean, the effect of urbanisation is negligible, whereas urbanisation plays an important role for South & Southeast Asia. However, in the case of moderate climate change (RCP4.5) combined with SSP3 high population growth and slow urbanisation, even in these regions wildfire activity may not increase during the 21st century. The arid Developing Middle East & North Africa region has a similar declining trend, with a reversal around the middle of the 21st century that is strongly dependent of climate scenario.

Two northern regions that belong to the middle-income group and therefore have lower population growth with SSP5 than with SSP3 (as have the tropical regions discussed so far) are Eastern Europe-Russia-Central Asia and Developing East Asia. For both, LPJ-GUESS-SIMFIRE simulates no trend during the historical period, except for an increasing upward trend beginning late in the 20th century. The climate scenario has a strong impact on both regions' predictions, and demographics a small, albeit still discernable one. In both regions, urbanisation plays an important role as seen in the difference between SSP2 with central and SSP2 with slow/fast urbanisation.

North America and High-Income Europe have a similar temporal profile as Eastern Europe-Russia-Central Asia, but with the order of demographic scenarios reversed. For North America, demographics are predicted to play only a minor role compared to climate change, but for High-Income Europe, there is still a marked influence even though changing the demographic scenario does not change the general trend in predictions. Here, differences between urbanisation scenarios are unimportant, but SSP5, which here has the highest population growth, leads to markedly higher predictions compared to SSP3 with low population growth. Another region that belongs to the high-income group but where most wildfire emissions are from the tropics (Australia & New Zealand, cf. Fig. 1) stands out as showing almost no change in fire activity across both centuries. Only for RCP8.5 there is a very slight increase, and difference between demographic scenarios have almost no impact on the results.

We also note that simulations with LPJ-GUESS-SIMFIRE sometimes differ substantially from GFED4.1s (Fig. 4, 5, Table 1), and show in particular higher emissions in the boreal zone (e.g. higher for Eastern Europe-Russia-Central Asia than for Latin America & Caribbean, and also high emissions for North America). We attribute this to differences in the assumed litter load and combustion completeness between GFED (van der Werf et al. 2010) and SIMFIRE (Knorr et al. 2012). These quantities are generally not well constrained, as noted by Knorr et al. (2012). We expect, however, that the relative change in emissions, which we compute by country (Table A1), is much less affected by those differences. In Fig. 6, we show this relative change from current conditions to 2090 by country/region for the two scenarios that

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lead to the lowest (SSP3 with RCP4.5) or highest (SSP5 with RCP8.5) end-century global emissions.

For SSP3/RCP4.5, there is again a very pronounced decline in fire activity in most but not all countries of Africa. South Africa, Namibia and in particular Botswana show a relative increase in emissions of up to 50%. The strongest decline is found in parts of West Africa, in particular Nigeria, where wildfires in this scenario almost completely disappear. By contrast, central Europe, which has a pronounced population decline under SSP3, shows a strong increase, albeit from a low base (Fig. 1). An arch of countries spanning from Turkey to Southeast Asia also show either a strong decline or only a small increase in fire activity. Western boreal North America (ALK, CAN-W, Table A1) and eastern boreal Russia (RUS-NW) show moderate to strong increases, which are much higher for SSP5/RCP8.5, driven mainly by climate change given the low population density in these regions. A very large increase with SSP5/RCP8.5 by around 150% is found for eastern and southern China (CHN-E), driven by reduced population size, fast urbanization, and climate change. A pronounced increase is found mainly for the northern part of the Amazon basin (BRA-N). For Australia, we find a decline in the north (AUS-N) for both climate scenarios, but a slight to pronounced increase for the remaining areas (demographics in this region play almost no role).

3.3 Predicted changes in emissions by population density

The strongest change in the distribution of wildfire emissions against population density (cf. Fig. A3) is found for Sub-Saharan Africa under the SSP3 and RCP4.5 scenarios, where the 0.1 to 1 and 1 to 10 people per km^2 categories see a decline by around a factor of 10 between 2010 and 2090 (Fig. 7). As the area extent of these categories hardly changes (dotted lines) and the decline is absent for SSP5/RCP8.5,

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the decrease is mainly because population density within a given category increases, which leads to more fire suppression. (Figs. 1, A2). Woody encroachment, which also leads to a decline in fire activity, would respond strongly to the higher CO_2 levels of RCP8.5 (Buitenwerf et al. 2012, Knorr et al. 2016b, c). Conversely, areas with more than 100 people per km^2 see an increase in both extent and emissions per area, as more people move into fire-prone area in this slow-urbanisation scenario. For the CLE anthropogenic-emissions scenario, we expect most changes in the relative dominance of wildfire vs. anthropogenic emissions to happen in the 10 to 100 people per km^2 category.

This pattern of increasing emissions in the most densely populated areas is seen for all middle to lower-income regions (all but Australia & New Zealand, North America and High-Income Europe). Of these, Latin America & Caribbean, Eastern Europe-Russia-Central Asia and Developing Middle East & North Africa show relatively small changes in emissions, while for South & Southeast Asia and Developing East Asia, a decline in emissions in sparsely populated regions is accompanied by a similar decline in anthropogenic emissions, so that no significant changes in the relative importance of the two emission sources are expected for this particular scenario. For High-Income Europe, wildfire emissions are projected to remain well below anthropogenic emissions in all categories, while for Australia & New Zealand, a continuing decrease in emissions in the most densely populated category will make wildfire emissions increasingly relevant in such areas. For North America simulated changes in wildfire are also minor and wildfires will continue to be the dominant source mainly in remote areas.

The situation of relative importance changes drastically if we consider the MFR anthropogenic scenario (Fig. 8). According to this scenario combined with RCP8.5

climate and SSP5 demographic change (rapid urbanisation, low population growth in low to middle income countries), wildfires could become the dominant emission source in Sub-Saharan Africa and Australia & New Zealand in all population-density categories as early as 2030, and be at least of comparable magnitude as anthropogenic emissions for Latin America & Caribbean and to a lesser extent South & Southeast Asia and Eastern Europe-Russia-Central Asia. High-Income Europe and Developing Middle East & North Africa, who both have the same increasing relationship between emissions and population density for both sources, wildfires will continue to be minor in all categories despite strong reductions in anthropogenic emissions. For Developing East Asia, there is an approximately fourfold increase predicted for wildfire emissions in the 10 to 100 inhabitants per km^2 category, with the result that they might become comparable to anthropogenic emissions in areas that comprise a rather large population.

3.4 Future patterns of pollutant exposure

The previous analysis only compared wildfire and anthropogenic emissions, but in some areas, both might be so low that they do not constitute a relevant health hazard. A further analysis therefore considers if wildfire emissions exceed a threshold of 0.5 g m^{-2} yr^{-1} (Fig. 9; see Fig. A4 and A5 for thresholds of 0.2 and 1 g m^{-2} yr^{-1}). Large areas in the boreal zone, South America, Central Asia and Australia where wildfires dominate do not reach this level. However, the analysis also reveals the demographic scenario as the main driver of change for Africa. For SSP3, with high population growth and slow urbanisation, many areas drop below this threshold in the future, independent of climate scenario, but not for SSP5 (low population growth and fast urbanisation). For northern Australia, the result is independent of demographic scenario, while RCP4.5 sees a small contraction of high-emission areas, but RCP8.5 a much larger one with an additional zone with high emissions emerging further south. Changes in the boreal zone and South America are slight but new high-emissions areas appear for RCP8.5 (light and dark blue). Larger new high-emission areas are found in southern China, mainly driven by demographic and to a lesser extent climate change. The same result is found for Portugal, but with the opposite demographic scenario as this is a high-income region where SSP5 has low population growth and leads to the extension of high-emission areas. Other temperate areas in North America and Australia see little change in any of the scenarios.

If we consider the number of people living in areas exceeding a certain wildfire-emissions threshold, we find an almost universal increase in both the absolute numbers, and the percentage of global population independent of climate and demographic scenario (Table 2). Currently, between 7.9 and 1.8% of world population is affected, depending on where the threshold is set (3.6% for the 0.5 g m^{-2} yr^{-1} threshold used with Fig. 10). Only for the 1 g m^{-2} yr^{-1} threshold and SSP5/RCP4.5 scenario, this percentage will very slightly decrease to 1.7% by 2030, but the absolute number still increase from 126 to 146 Million people affected by dangerously high levels of wildfire air pollution. For all other scenarios and for SSP5/RCP4.5 from 2050 there will be an increase both in the absolute and relative numbers of affected population. The demographic scenario is also more important than the degree of climate change. For the 0.5 g m^{-2} yr^{-1} threshold, changing the RCP scenario changes the percentage by between 0.1 for 2030 and 0.4 for 2090, but changing from SSP5 (low growth, fast urbanisation) to SSP3 (high growth, slow urbanisation) changes the percentage of affected population by between 0.4 for 2030 and 1.2 for 2090. This difference is even more pronounced for the 0.2 g m^{-2} yr^{-1} threshold, while for the 1 g

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m^{-2} yr^{-1} threshold, both climate and demographic change have about the same importance.

Absolute numbers of people affected by the intermediate 0.5 g m^{-2} yr^{-1} threshold can reach as high as 973 Million for SSP3 with high population growth and slow urbanisation combined with RCP8.5 climate change, from currently 256 Million, i.e. almost four times the current estimate. Finally, the spatial exceedance patterns are predicted to change very little for 0.2 g m^{-2} yr^{-1} (Fig. A4), but are similar between the 0.2 and 0.5 g m^{-2} yr^{-1} cases (Fig. A5). This stands in contrast to the percentage of affected population (Table 2), and can be explained by a change in the geographic location of areas that are either added or subtracted (cf. China in Fig. A4 vs. Africa in Fig. A5).

Using the idealized conditions that have led us to the 0.5 g m^{-2} yr^{-1} threshold, i.e. 1000 m boundary layer height and 1/50 yr life time of PM2.5, we can calculate a mean annual concentration value for every grid cell and from there a population-weighted average for each of the nine world regions. For six of those regions, the resulting concentration is below 1 µg m^{-3} for all years and scenarios and therefore not considered relevant. For the other three, results are shown in Table 3. For Latin America & Caribbean, we only find a small increase, mainly for RCP8.5. For Australia & New Zealand, the increase is more substantial and much higher for RCP8.5, and the results for both regions are almost the same across all demographic scenarios. Both findings are in accordance with Fig. 10. For Sub-Saharan Africa, however, we find a universal decrease in exposure estimates from currently 7.7 to as low as 5.3 µg m^{-2} by 2090 for SSP3 with high population growth, slow urbanisation and RCP8.5. Differences between RCP scenarios amount to about 0.1 µg m^{-2}, but between demographic scenarios to between 0.3 for RCP4.5 by 2030, and 1.3 for

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RCP4.5 by 2090. There is also a reversal of the order compared to the population affected by the 0.5 g m^{-2} yr^{-1} threshold, which we assume is dominated by Sub-Saharan Africa (Table 1). Here, the idealized exposure in Sub-Saharan Africa is higher for the fast-urbanisation/low population growth scenario (SSP5) than for those with slow-urbanisation/high population growth (SSP3), but the reverse is true for both relative and absolute population in high-emission areas. For both measure of human risk from PM2.5 exposure (Tables 1 and 2), changing only the urbanisation scenarios (with the same SSP2 population scenario) has a markedly smaller impact than changing only the population scenario (and keeping either fast or slow urbanisation).

4 Discussion

An important question is whether past climate change has already led to increases in wildfire activity and related pollutant emissions. The many uncertainties associated with modelling wildfire emissions are discussed in detail by Knorr et al. (2012, 2016a). This study simulates an increase from around 1980 to 1990 for Russia and North America, which seems to agree with the observation of a climate-driven increase in fire activity in the western U.S. based on data from 1982 to 2012 (Westerling, 2016). However, our simulated relative increase is only very slight for the western U.S. region (Fig. A6), and only reaches about 20% by 2090 for RCP8.5 (Fig. 6). Doerr and Santin (2016) argue that this increase may be regional and highly policy dependent. Ironically, there is the possibility that the increase has been driven by increased fire suppression, which has led to fewer but more intense fires and more area burned. While past climate-driven increases in fire activity remain debatable, this study shows a general picture of climate-driven increases that may be overridden by demographic changes only in Sub-Saharan Africa.

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A particularly large relative increase in wildfire emissions is projected for China and the boreal areas of North America and Russia for the RCP8.5 climate scenario. Southern China is also identified as a new area of high risk from wildfire air pollution. While forest fires in China may have received less attention, they can still be substantial, with 670,000 ha area burnt annually between 1950 and 1999 (Shu et al. 2003).

The present study broadly re-confirms the results of a previous analysis that was based on burned area as a measure of wildfire risk (Knorr et al. 2016c). Sub-Saharan Africa, currently by far the most fire-prone region, is projected to see a demographically driven decline in fire activity, except for a scenario of low population growth and rapid urbanisation. This decline is in agreement with observations of declining burned area linked to demographic trends for northern part of Sub-Saharan Africa (Andela and van der Werf, 2014). At the same time, wildfire risk to humans will broadly increase for almost all scenarios considered. For developing countries, differences between the high and low population growth scenarios tend to be more important for the projected changes in fire hazard than differences between the two climate scenarios. For the developed world and northern wildfire regions, climate and vegetation change appear to be the main drivers.

There are some noteworthy differences between the approaches. Fire risk in Knorr et al. (2016c) is based on the probability of a point in space to be affected by wildfire, while the present study focuses on emissions-related hazards and uses PM2.5 emissions as an indicator, taking into account the amount of fuel burnt and its efficiency at producing PM2.5. Both aspects are important for how human societies are impacted by fire but represent different types of hazard, as the former relates mainly to potential loss of property, whereas the latter affects human health. While the burned-area study uses output from LPJ-GUESS-SIMFIRE directly, the present one uses observation-based estimated and re-scales them based on smaller regions according to LPJ-GUESS-SIMFIRE projections. This approach has been used before by Knorr et al. (2016a) and accounts for the importance of policy on wildfire occurrence by scaling emissions mostly by country. The importance of policy is evident for example when comparing observed burned area in Scandinavia to adjacent areas of Russia (Giglio et al. 2013). There is also an underlying assumption in both studies that the impact of population density on area burnt within each country is invariant over time. The present study also confirms the important role of PM2.5 emissions for wildfire air pollution risks, as other pollutants tend to have a larger relative contribution from anthropogenic sources (Knorr et al. 2016a).

LPJ-GUESS-SIMFIRE only simulates wildfires. The predictions presented in this study therefore leave out the possibility of significant increases in deforestation or peat fire sources. Therefore, peat and deforestation fires have been excluded from the predictive part of the present study. Peat fires can be associated with considerable emissions (Page et al. 2002, Kajii et al. 2002), and forest conversion is often accompanied by burning (van der Werf et al. 2010). The comparative analysis shown here, however, shows that globally both are of minor importance except for Southeast Asia. The south-east Asian deforestation and peat fires occur mainly in Indonesia (Field et al. 2009), where they are the dominant pollution source and occur even in more densely populated areas. In other world regions, including Russia, peat fires are of minor importance.

Whether or not future land-use change will lead to an increase or a decrease in deforestation, is unknown. Based on four integrated-assessment model realisations of the four RCPs, Hurtt et al. (2011) projected little increase, and if any, then in future

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crop and pasture areas. However, in studies that examined land-use change from a broader perspective, a much larger range of crop and pasture changes emerged (Eitelberg et al. 2015, Prestele et al. 2016), which makes the relative change of deforestation and wildfires highly uncertain. In the present analysis, declining wildfire emissions are only predicted for Sub-Saharan Africa, where it appears to be related to conversion of savanna to cropland (Andela and van der Werf 2014). Interestingly, increased fire activity is predicted for southern Africa for both climate scenarios, in accordance with the result of Andela and van der Werf, who found a recent increase for that region driven by declining precipitation. We therefore believe that the results of the present study are broadly representative of possible future changes in wildfire risk, even though one needs to take into account that in certain areas, deforestation may remain the main driver of air pollution for a while.

Demographic trends will be an important and often the main factor driving changes in wildfire hazards. One factor is that higher population density in rural areas means lower burned area and emissions, but also more people exposed, and vice versa. In the analysis of burned area patterns by Knorr et al. (2016a), there was a large impact of urbanisation (using the same SSP2 per-country population scenario), with more people living in fire prone areas at slow than at fast urbanisation, but with a relatively minor affect due to overall population change. The average fractional surface area burned in densely populated areas was also higher for slower urbanisation. This is because the suppression of fire by higher population density was over-compensated by a higher number of people living in rural, fire-prone areas. In the present analysis, we find a much smaller impact of urbanisation on the number of people living in areas with high wildfire emissions, but a large impact of total population change. Even though more people tend to suppress fire, the percentage of people living in high-emission areas increases when the overall population is higher. This is the opposite of what we find for the average pollutant concentration levels experienced by the population: For Sub-Saharan Africa, fast urbanisation or high population growth lead to higher emissions in rural areas and overall higher exposure to wildfire pollutants even though people move away from areas with high wildfire activity.

While any additional emission source of PM2.5 poses a health risk (WHO 2005), in practice wildfires are likely to be ignored by air quality policy if they emit considerably less than anthropogenic sources, in particular as their occurrence tends to be sporadic and of short-term nature. One factor is that wildfire emissions are much more difficult to legislate given the sometimes unexpected results of fire suppression policies (Donovan and Brown 2007). However, we find that in large parts of the world, wildfires are the main air pollutant source. While in many of those regions, wildfires dominate by absence of large anthropogenic sources, Sub-Saharan Africa, Brazil, northern Australia, Southeast Asia and the boreal zone are regions where they not only emit more PM2.5 than anthropogenic sources, but emissions are higher than some approximate threshold of health relevance in the region of 0.5 to 1 g m^{-2} yr^{-1}. This implies that even controlling all anthropogenic sources, the WHO air quality goals can not be attained.

It will therefore of critical importance whether future air quality policy objectives in the various regions will converge to the current WHO guidelines, in which case in these regions fire management will become increasingly important. At current legislation, wildfires will seize to be important for large parts of Africa and considerable parts of South America. If, however, anthropogenic emissions are aggressively curtailed (MFR scenario), wildfires in both regions are predicted to

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decline less than anthropogenic sources, and climate change will even lead to new areas with wildfire emission levels relevant for air quality policy. Such reductions in anthropogenic emissions would bring those down to levels similar to those of wildfires even in the most densely populated areas, making wildfires the most important pollution source in many regions (Sub-Saharan Africa, Latin America & Caribbean, and to a lesser degree Australia & New Zealand, Eastern Europe-Russia-Central Asia). Because past efforts aimed at a lasting reduction in wildfire activity have largely failed despite high costs (Doerr and Santin 2016), it is questionable whether it is even possible to devise policy measure aimed at bringing down wildfire emissions to meet WHO guidelines. Because wildfires are an essential part of many ecosystems (Bowman et al. 2009), it may therefore better to discount for wildfire emissions as a natural phenomenon and rather adapt urban and suburban planning accordingly (Moritz et al. 2014).

This study has some important limitations. It does not consider atmospheric transport or injection height (Gonzi et al. 2015, Sofiev et al. 2012), nor horizontal advection of pollutants, and predictions are based on a single fire and vegetation model. Demographic scenarios do not currently account for changes in the urban mask. It only considers climatological annual emissions during specified time windows, even though wildfires impacts on air quality can have large interannual (Jaffe et al. 2008) and intra-seasonal variations, caused in part by long-range transport (Niemi et al. 2005), which is also not accounted for. It also does not account for relevant secondary emission products, such as ozone from wildfires, which can reach policy relevant levels (Jaffe and Wigder 2012). This contrasts with previous studies on the possible impact of climate change on wildfire-related air pollution hazards have concentrated on changes in meteorological conditions (Jacob and Winner 2008,

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Tai et al. 2010) instead of emissions. The study by Kaiser et al. (2012) focuses on current conditions and includes atmospheric transport, using satellite-observed fire radiative energy (Wooster et al. 2005) as well as satellite-derived aerosol optical depth data to constrain wildfire emissions (Kaiser et al. 2012), as opposed to satellite-derived burned area as used by GFED (van der Werf et al. 2010, Giglio et al. 2013). There is also recent progress in the incorporation of injection height (Sofiev et al. 2012) into chemistry-enabled atmospheric general circulation models (Veira et al. 2015).

By contrast, the present study focuses on changes in emissions, and is the first global-scale study to consider changes both climate and demographic drivers of air pollutant emissions from wildfires. Future work should aim at using general circulation models with realistic plume heights for a series of dedicated present and future time slices at combining observed plume height information, fire radiative energy data (for their finer temporal resolution), satellite-derived burned area (for better spatial coverage), projected emission changes from coupled dynamic vegetation-fire models (as the present study), and improved demographic scenarios accounting for changes in urban population density. Such studies would then not only account for long-range transport pollutants and secondary products such as ozone, but also simulate the temporal statistics of pollution events on a daily time scale. Such results could then be used, for example, to assess for how many days the WHO 24-hour PM2.5 limit (WHO 2005) is a exceeded as a result of wildfire emissions.

5 Summary and conclusions

- So far, there does not seem to be compelling evidence for a long-term trend towards increased pollutant emissions from wildfires due to climate warming. While in the Western U.S. burned area from wildfires seems to have increased and the increase may be linked to climate, the present study simulates only very small relative increase for the region. Most of the predicted increase for North America concerns the boreal forest zone.

- Demographic changes appear to be the main driver for the expected changes in wildfire emissions in Sub-Saharan Africa. For a scenario of high population growth and slow urbanisation, there will be large decreases in emissions in many parts of the continent, often dropping below thresholds that make them relevant for air quality policy. The decrease will be much smaller or turn into an increase for a scenario of low population growth and fast urbanisation.
- Exposure of humans to PM2.5 in Sub-Saharan Africa is expected to drop for all demographic scenarios, but mostly for high population growth and slow urbanisation. Stronger fire suppression by higher rural population outweighs the effect of larger populations in rural areas.
- Globally, both the number of people and the percentage of world population exposed to dangerously high PM2.5 emissions from wildfires is expected to increase in all scenarios considered. Both relative and absolute increase are highest for high population growth, while the degree of urbanisation plays only a minor role. This is opposite to the average fractional burned area in densely populated regions – a measure of fire risk to properties and lives – where the projected increase was earlier found to depend mostly on the degree of urbanisation.
- The goal of reducing PM2.5 emissions globally such that the WHO guidelines for PM2.5 concentrations are met everywhere may not be attainable because in many regions wildfire emissions will remain above critical thresholds. So far, there is no generally accepted method for wildfire management that has been

shown to lead to lasting reductions in fire activity or emissions. The still widely used approach of aggressive fire suppression is not only costly, but may even have led to increased overall fire activity. It may therefore be prudent to accept the existence of wildfires as a natural phenomenon with important ecosystem function and adapt urban planning accordingly.

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Tables

Table 1: Emissions [Gg/yr] by world region from various sources

Region	Wildfire[1]	Deforestation[1]	Peat fire[1]	Anthropogenic[2]	Wildfire[1]	Deforestation[1]	Peat fire[1]	Anthropogenic[2]
	PM2.5				NOx			
Sub-Saharan Africa	14,973	538	0	5,864	8,141	151	0	2,169
Latin America & Caribbean	3,138	1,886	0	2,534	1,655	528	0	4,956
Easter Europe-Russia-Central Asia	2,832	0	18	2,490	265	0	9	5,967
South & Southeast Asia	1,593	1,499	598	10,392	791	420	297	6,155
Australia & New Zealand	1,536	22	0	186	747	6	0	834
North America	1,349	0	30	1,462	126	0	15	13,654
Developing East Asia	364	17	0	13,324	73	5	0	11,587
High-income Europe	31	0	0	1,630	13	0	0	7,216
Developing Middle East & North Africa	7	0	0	1,561	4	0	0	4,236
Globe	25,842	3,968	646	40,370	11,822	1,112	321	59,652
	CO				BC			
Sub-Saharan Africa	131,545	5,500	0	69,581	773	31	0	801
Latin America & Caribbean	27,315	19,270	0	41,113	160	108	0	344
Easter Europe-Russia-Central Asia	23,461	0	286	27,338	97	0	2	338
South & Southeast Asia	13,623	15,319	9,739	98,011	80	86	72	1,217
Australia & New Zealand	13,056	221	0	4,503	76	1	0	33
North America	10,976	0	496	64,754	46	0	4	324
Developing East Asia	2,886	173	3	146,050	14	1	0	1,559
High-income Europe	250	0	0	27,150	1	0	0	357
Developing Middle East & North Africa	59	0	0	23,898	0	0	0	248
Globe	223,331	40,557	10,524	518,576	1,249	227	77	5,397

[1] *GFED4.1s*
[2] *ECLIPSE-GAINS 4a*

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Table 2: Global population affected by wildfire PM2.5 emissions above given limit.

Population	Urbanization			RCP4.5						RCP8.5					
Limit [g m^{-2} yr^{-1}]	0.2														
		Current	%[1)]	2030	%	2050	%	2090	%	2030	%	2050	%	2090	%
SSP5	fast			721	8.6	892	10.0	1054	12.5	721	8.6	888	9.9	1080	12.8
SSP2	fast			771	8.9	1032	10.6	1498	14.5	775	8.9	1034	10.6	1531	14.9
SSP2	central	568	7.9	780	9.0	1042	10.7	1466	14.2	782	9.0	1037	10.7	1537	14.9
SSP2	slow			787	9.1	1045	10.8	1468	14.3	785	9.0	1042	10.7	1560	15.1
SSP3	slow			844	9.3	1302	12.1	2221	16.0	842	9.3	1273	11.9	2299	16.6
Limit [g m^{-2} yr^{-1}]	0.5														
SSP5	fast			313	3.7	384	4.3	456	5.4	317	3.8	391	4.4	489	5.8
SSP2	fast			333	3.8	441	4.5	646	6.3	337	3.9	451	4.6	681	6.6
SSP2	central	256	3.6	340	3.9	446	4.6	636	6.2	341	3.9	452	4.7	682	6.6
SSP2	slow			349	4.0	455	4.7	629	6.1	348	4.0	454	4.7	688	6.7
SSP3	slow			372	4.1	531	4.9	911	6.6	374	4.1	528	4.9	973	7.0
Limit [g m^{-2} yr^{-1}]	1														
SSP5	fast			146	1.7	176	2.0	204	2.4	148	1.8	171	1.9	219	2.6
SSP2	fast			154	1.8	193	2.0	280	2.7	155	1.8	188	1.9	302	2.9
SSP2	central	126	1.8	156	1.8	187	1.9	267	2.6	158	1.8	187	1.9	291	2.8
SSP2	slow			162	1.9	194	2.0	247	2.4	162	1.9	192	2.0	266	2.6
SSP3	slow			173	1.9	211	2.0	330	2.4	172	1.9	209	2.0	351	2.5

[1)] Per cent of global population

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Table 3: Average annual exposure of population to PM2.5 [μg m^{-3}] under idealized conditions.

Population	Urbanization	Current	RCP4.5 2030	RCP4.5 2050	RCP4.5 2090	RCP8.5 2030	RCP8.5 2050	RCP8.5 2090
Sub-Saharan Africa								
SSP5	fast		6.6	6.5	6.4	6.6	6.3	6.5
SSP2	fast		6.5	6.2	6.0	6.5	6.0	6.1
SSP2	central	7.7	6.5	6.0	5.7	6.5	5.9	6.0
SSP2	slow		6.4	5.8	5.4	6.4	5.7	5.7
SSP3	slow		6.3	5.6	5.1	6.2	5.5	5.3
Australia and New Zeeland								
SSP5	fast		3.2	3.5	3.6	3.2	3.5	3.9
SSP2	fast		3.2	3.5	3.6	3.2	3.5	4.0
SSP2	central	3.1	3.2	3.5	3.6	3.2	3.5	4.0
SSP2	slow		3.2	3.5	3.6	3.2	3.5	4.0
SSP3	slow		3.2	3.5	3.7	3.2	3.5	4.1
Latin America and Caribbean								
SSP5	fast		1.5	1.6	1.7	1.5	1.6	1.9
SSP2	fast		1.5	1.5	1.6	1.5	1.6	1.8
SSP2	central	1.5	1.5	1.5	1.6	1.5	1.6	1.8
SSP2	slow		1.5	1.5	1.6	1.5	1.6	1.8
SSP3	slow		1.5	1.5	1.5	1.5	1.5	1.7

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Figures

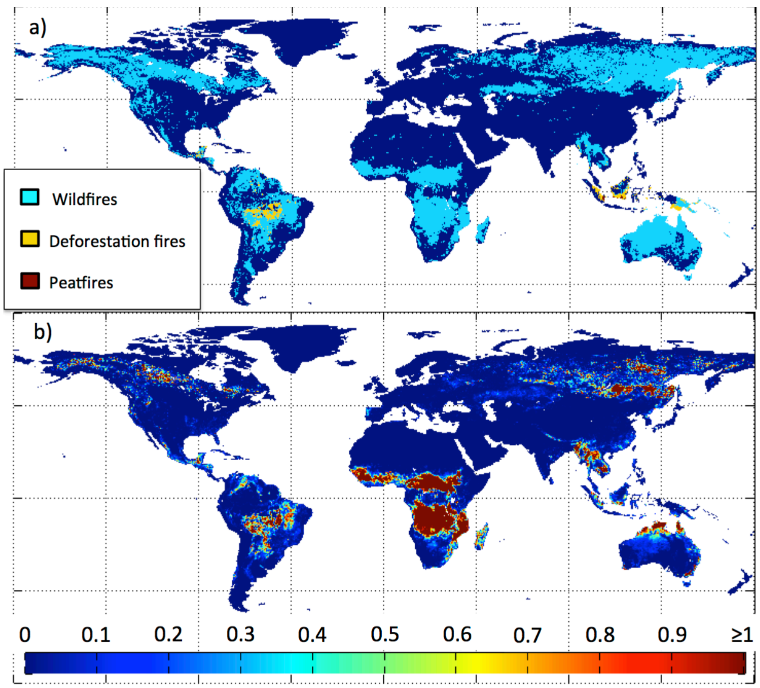
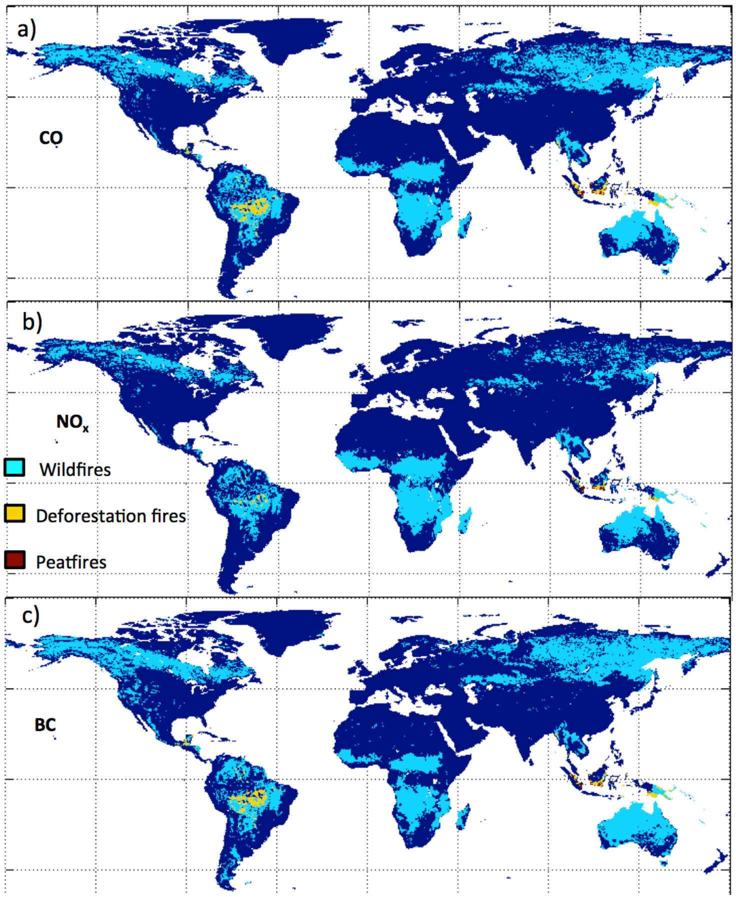


Figure 1: a) Largest current source of PM2.5 emissions, including anthropogenic sources (dark blue areas); b) wildfires emissions in g PM2.5 m^{-2} yr^{-1}. Average annual PM2.5 emissions 1997 to 2014 are from to GFED4.1s, or ECLIPSE GAINS 4a for 2010 (anthropogenic).

912 

913 *Figure 2: Largest current source of annual air pollutant emissions. Dark blue areas:*
914 *dominant source anthropogenic, or zero emissions. a) CO, b) NO_x, c) black carbon.*

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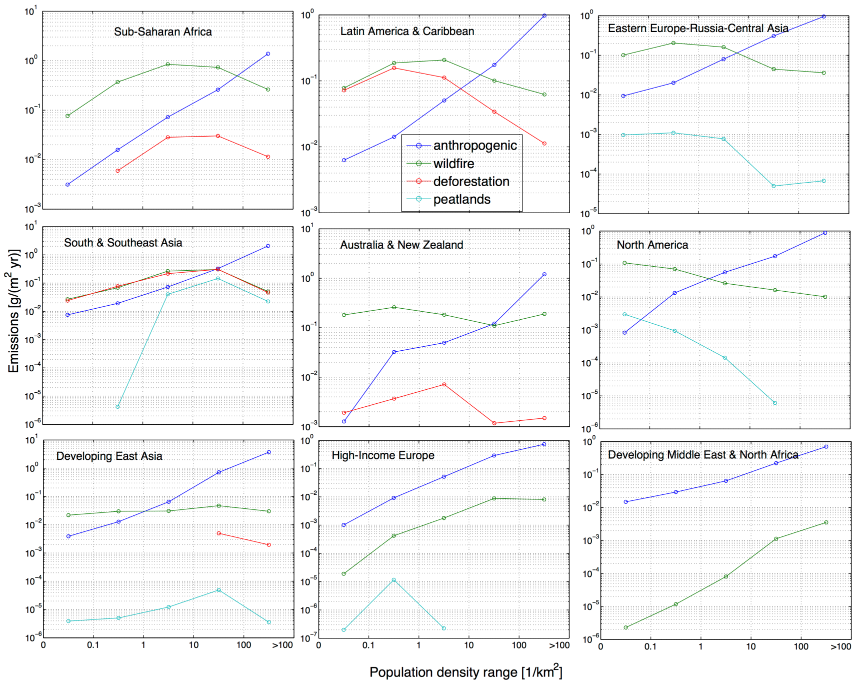

Figure 3: Comparison of current anthropogenic, wildfire, deforestation fire and peat fire PM2.5 emissions by region and range population density, constructed by relating emission rates to the population density found for the same grid box on a 0.5 by 0.5 degree grid. Emissions are from ECLIPSE GAINS 4a (anthropogenic source for 2010) and GFED4.1s (average of 1997-2014).

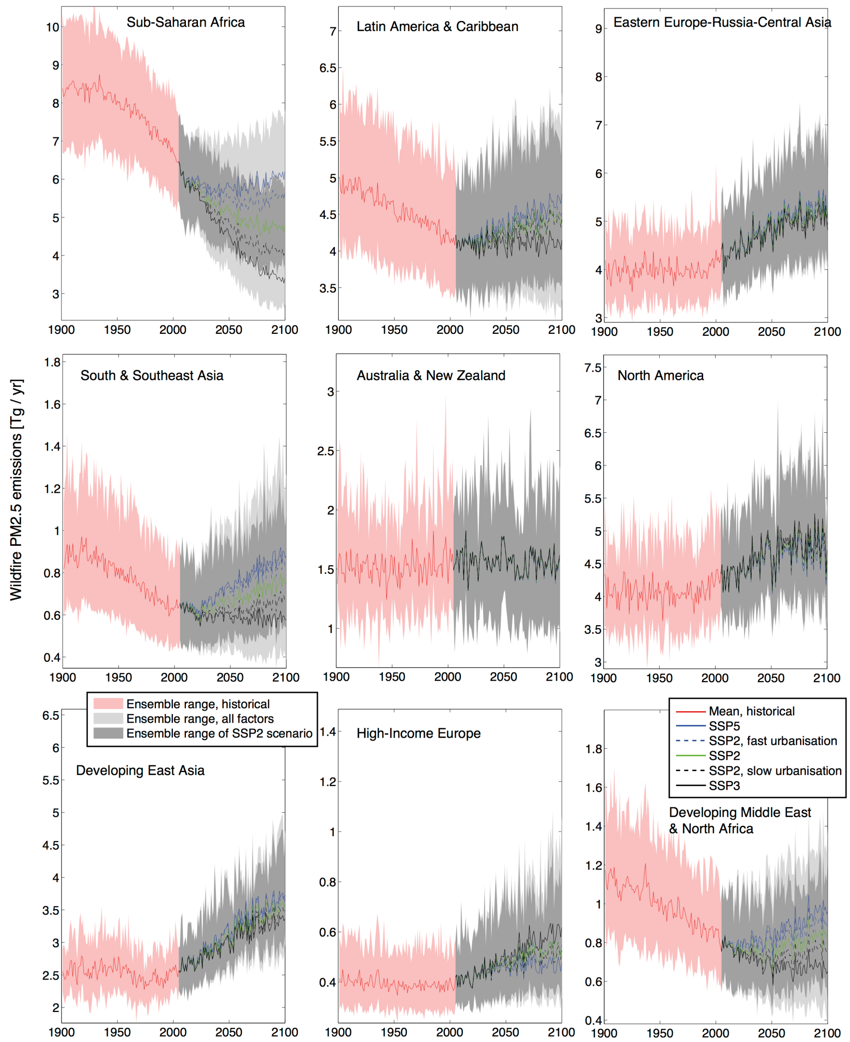

Figure 4. Annual PM2.5 emissions from ensemble of LPJ-GUESS-SIMFIRE simulations for nine world regions 1901 to 2100. Ensemble ranges and impact of population and urbanisation scenarios. Climate scenario: RCP4.5.

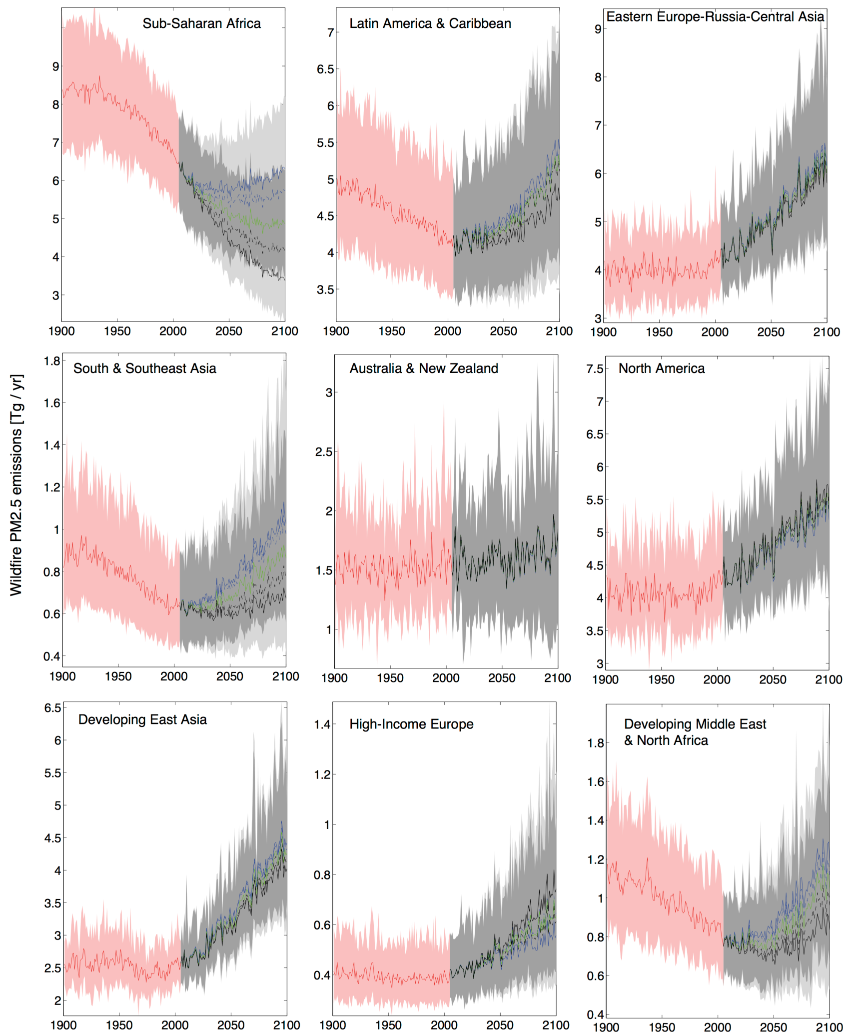

Figure 5. Same as previous figure, but for climate scenario RCP8.5.

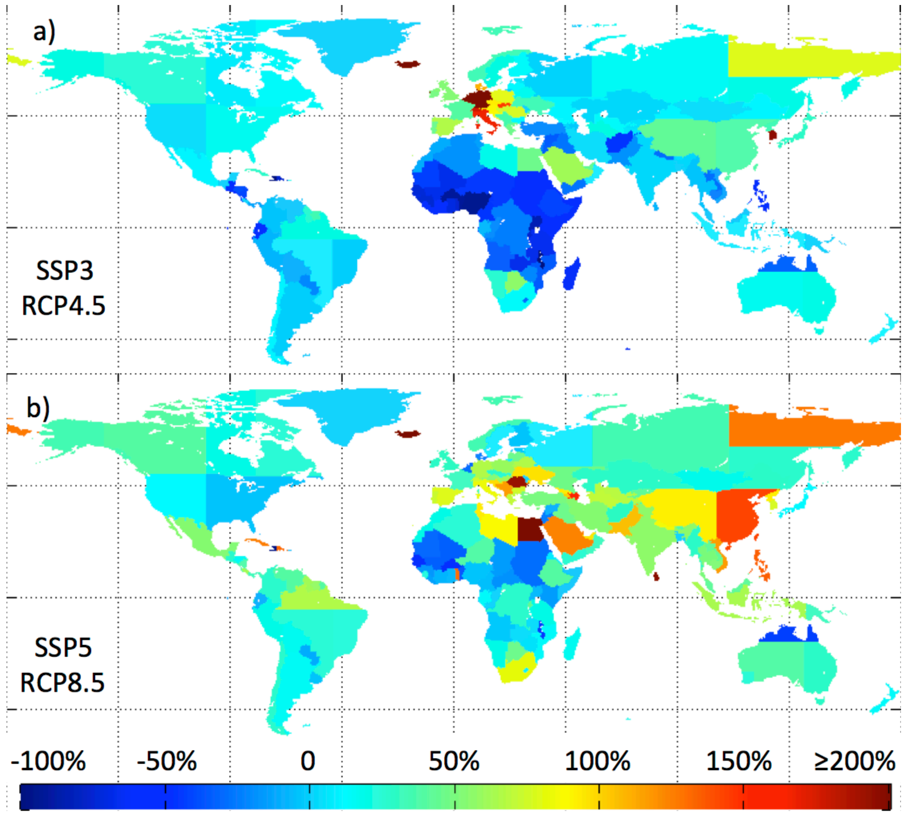

Figure 6: Relative change in annual PM2.5 emissions from current (1997-2014 mean) to 2090 (2080 to 2100 mean) by country/region. a) SSP3 globally high population growth (high-income countries: low population growth) with slow urbanisation and RCP4.5 climate scenario, b) SSP5 globally low population growth (high-income countries: high population growth) with slow urbanisation, RCP8.5 climate scenario.

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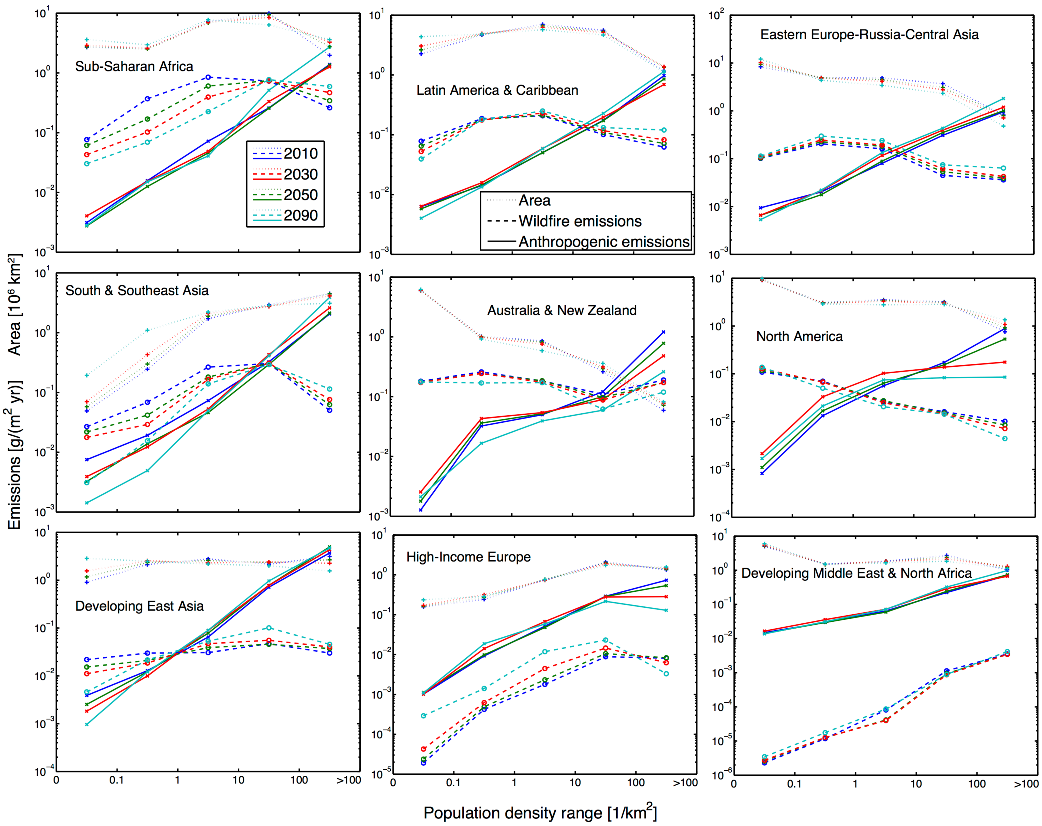
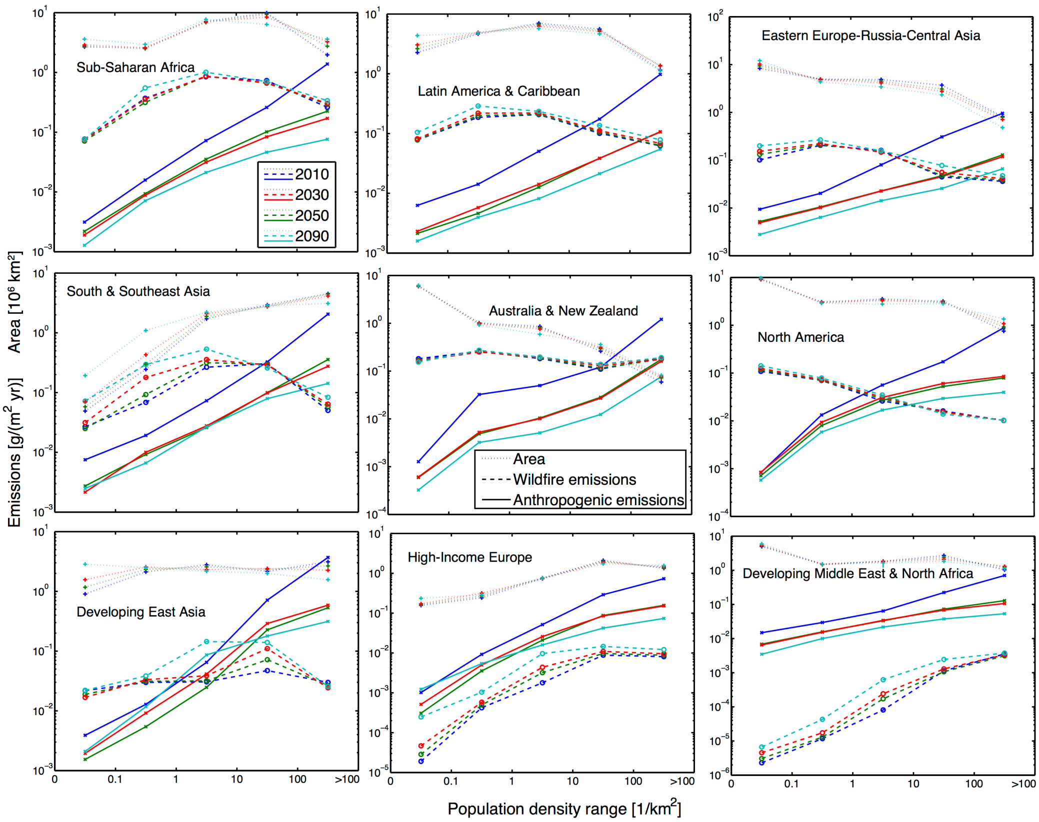


936

937 *Figure 7: Predicted changes of annual PM2.5 emissions against ranges of population density from*
938 *wildfires and anthropogenic sources, as well as changes in area extent of the population-density*
939 *categories, for the nine world regions, based on re-scaled GFED4.1s wildfire emissions. SSP3*
940 *demographic scenario, RCP4.5 climate change and Current-Legislation (CLE) anthropogenic*
941 *emissions scenario.*

942



943

944 *Figure 8: As previous figure, but for SSP5 demographic scenario, RCP8.5 climate change and*

945 *Maximum Feasible Reduction (MFR) anthropogenic-emissions scenario.*

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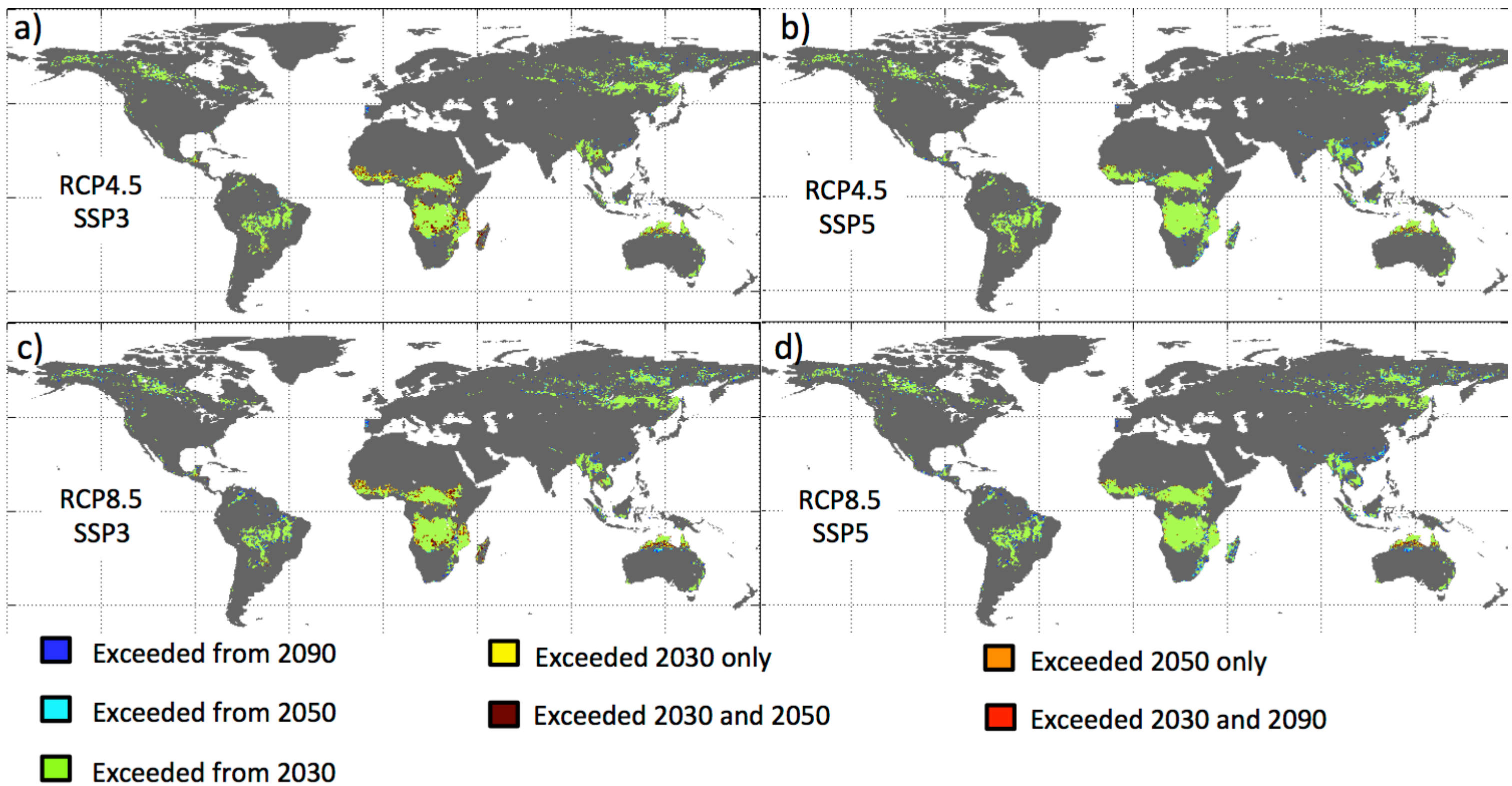

Figure 9: Timing of when annual wildfire emissions exceed 0.5 g PM2.5 m^{-2} yr^{-1} for the time windows 2030, 2050 and 2090a, b) RCP4.5 and c, d) RCP8.5 climate scenario; a, c) SSP3 and b, d) SSP5 demographic scenario.

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Appendix

Table A1: Countries/regions used for scaling GFED4.1s wildfire emissions.

Code	Country name	World region	grid cells on 1-degree grid	non-crop cells[1]
AGO	Angola	Sub-Saharan Africa	100	100
BEN	Benin		10	6
BWA	Botswana		46	46
BFA	Burkina Faso		23	21
BDI	Burundi		3	3
CMR	Cameroon		37	35
CAF	Central African Republic		49	46
TCD	Chad		100	100
COG	Congo		24	24
ZAR	Congo, Dem. Republic		176	176
CIV	Cote d'Ivoire		25	24
ERI	Eritrea		12	12
ETH	Ethiopia		90	89
GAB	Gabon		20	20
GHA	Ghana		18	13
GIN	Guinea		20	20
GNB	Guinea-Bissau		1	1
KEN	Kenya		41	40
LSO	Lesotho		1	1
LBR	Liberia		5	5
MDG	Madagascar		43	43
MWI	Malawi		10	10
MLI	Mali		106	106
MRT	Mauritania		80	80
MOZ	Mozambique		61	60
NAM	Namibia		66	66
NER	Niger		94	80
NGA	Nigeria		74	40
SEN	Senegal		17	16
SLE	Sierra Leone		5	5
SOM	Somalia		55	55
ZAF	South Africa		99	98
SDN	Sudan		207	199
TGO	Togo		2	1
UGA	Uganda		16	13
TZA	Tanzania		73	72
ZMB	Zambia		63	63
ZWE	Zimbabwe		30	30
DZA	Algeria	Developing Middle East and North Africa	189	184
EGY	Egypt		77	76
LBY	Libya		131	131
MAR	Morocco		56	49
TUN	Tunisia		14	11
AFG	Afghanistan		53	52
IRN	Iran		134	129
IRQ	Iraq		37	31
JOR	Jordan		6	6
SAU	Saudi Arabia		154	154
SYR	Syria		15	9
TUR	Turkey		57	44
YEM	Yemen		31	31
AUT	Austria	High-income Europe	7	7
BNL	Benelux		5	3
CRS	Croatia and Slovenia		3	2
CZE	Czech Republic		5	3
DNK	Denmark		6	3
EST	Estonia		4	4
FIN	Finland		28	27
FRA	France		41	24
DEU	Germany		32	29
GRC	Greece		10	9
HUN	Hungary		7	2
ISL	Iceland		7	7
IRL	Ireland		5	4
ITA	Italy		23	11
NOR	Norway		31	31
POL	Poland		25	11
PRT	Portugal		6	5
SVK	Slovakia		6	2
ESP	Spain		40	24
SWE	Sweden		39	39
CHE	Switzerland		2	2
GBR	United Kingdom		19	13

Code	Country name	World region	grid cells on 1-degree grid	non-crop cells	longitude range	latitude range
ARM	Armenia	Eastern Europe, Russia and Central Asia	4	4		
AZE	Azerbaijan		7	6		
GEO	Georgia		6	6		
KAZ	Kazakstan		213	206		
KGZ	Kyrgyzstan		16	16		
TJK	Tajikistan		8	8		
TKM	Turkmenistan		35	35		
UZB	Uzbekistan		35	32		
BLR	Belarus		16	14		
BGR	Bulgaria		10	8		
LLI	Latvia and Lithunania		10	5		
ROM	Romania		19	10		
RUS-SW			78	32	W of 60°E	S of 52°N
RUS-NW			212	150	W of 55°E	N of 52°N
RUS-C	Russian Federation		553	506	not in other RUS	
RUS-SE			232	232	E of 110°E	S of 60°N
RUS-NE			327	327	E of 110°E	N of 60°N
UKR	Ukraine		47	5		
YUA	Serbia, Montenegro, Bosnia, Macedonia		13	11		
CHN-W		Developing East Asia	348	342	W of 105°E	
CHN-E	China		283	211	E of 105°E	S of 43°N
CHN-N			122	103		N of 43°N
PRK	North Korea		10	8		
MNG	Mongolia		131	131		
BTN	Bhutan	South and South-East Asia	4	2		
KHM	Cambodia		14	13		
IND	India		256	50		
IDN	Indonesia		125	116		
LAO	Laos		18	18		
MYS	Malaysia		23	23		
MMR	Myanmar		44	36		
NPL	Nepal		12	8		
PAK	Pakistan		58	44		
PHL	Philippines		16	14		
LKA	Sri Lanka		4	4		
THA	Thailand		42	30		
VNM	Viet Nam		27	22		
PNG	Papua New Guinea		31	31		
AUS-SW		Australia and New Zealand	18	16	W of 120°E	S of 30°S
AUS-E	Australia		200	178	E of 140°E	S of 18°S
AUS-C			317	316	not in other AUS	
AUS-N			76	76		N of 18°S
NZL	New Zealand		22	22		
CAN-W		North America	385	341	W of 100°W	
CAN-C	Canada		192	185	100...80°W	
CAN-E			176	176	E of 80°W	
USA-W			314	294	W of 100°W	
USA-E	United States of America		372	222	E of 100°W	
ALK			116	116		N of 50°N
CRI	Costa Rica	Latina America and Caribbean	3	3		
CUB	Cuba		7	5		
DOM	Dominican Republic		4	4		
GTM	Guatemala		15	15		
HTI	Haiti		2	2		
HND	Honduras		9	9		
MEX-W	Mexico		120	115	W of 95°W	
MEX-SE			19	19	E of 95°W	
NIC	Nicaragua		8	8		
PAN	Panama		6	6		
ARG	Argentina		230	207		
BOL	Bolivia		88	88		
BRA-W			197	192	W of 49°W	S of 5°S
BRA-E	Brazil		316	294	E of 49°W	
BRA-N			161	161		N of 5°S
CHL	Chile		61	60		
COL	Colombia		88	88		
ECU	Ecuador		19	19		
GUF	French Guiana		6	6		
GUY	Guyana		15	15		
PRY	Paraguay		28	28		
PER	Peru		100	100		
SUR	Suriname		11	11		
URY	Uruguay		15	15		
VEN	Venezuela		73	73		
ISR	Israel	-	4	4		
JPN	Japan		28	28		
KOR	South Korea		6	6		
OMN	Oman		26	26		
ARE	United Arab Emirates		8	8		
MDA	Republic of Moldova[2]		4	0		
BGD	Bangladesh[2]		10	1		
GRL	Greenland[3]		31	31		

[1]Cells with less than 50% cropland fraction in past or future scenarios
[2]Constant emissions assumed because dominated by croplands
[3]Constant emissions assumed because zero current wildfire emissions in some simulations

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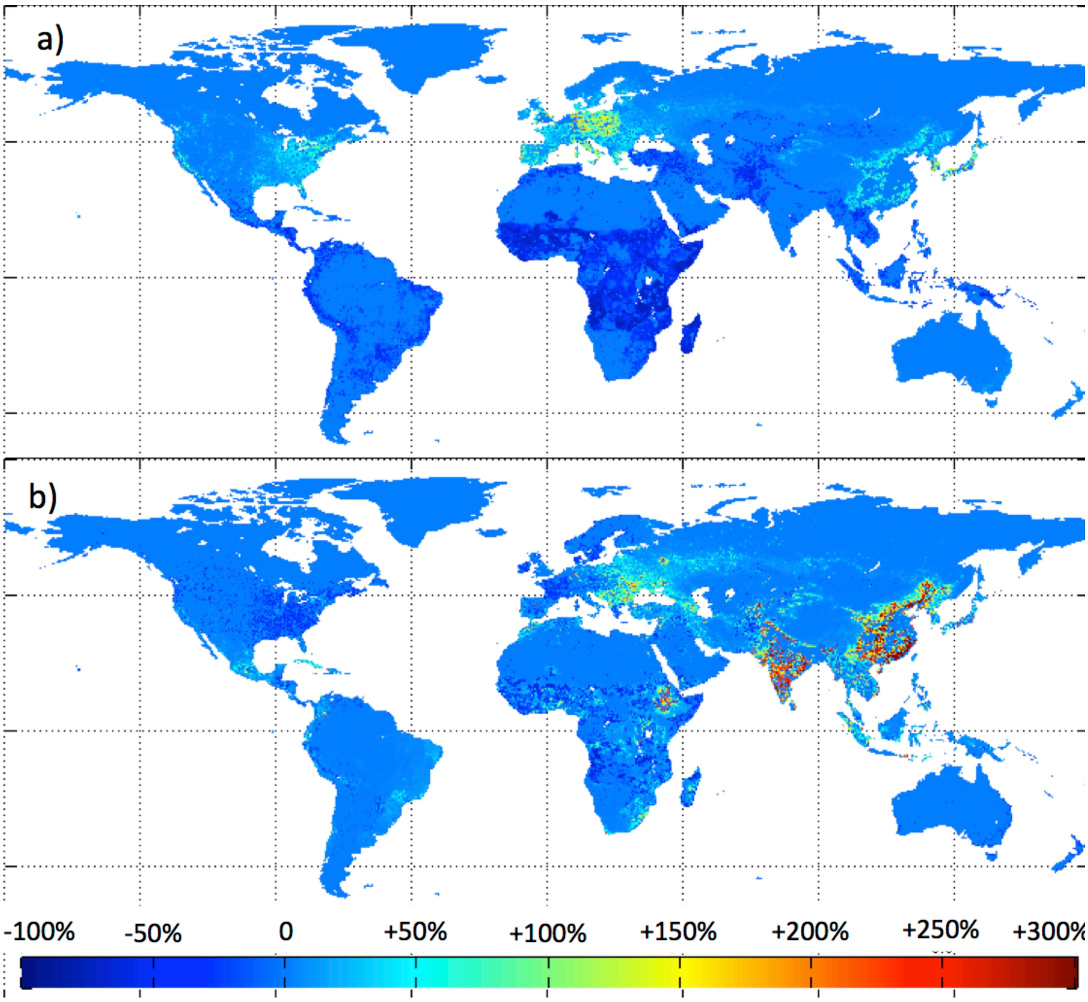

952

953 *Figure A1: Relative change in wildfire emissions due to changes in population density from 2010 to*
954 *2090 according to Equ. 2. a) SSP3, b) SSP5 demographic scenario.*

955

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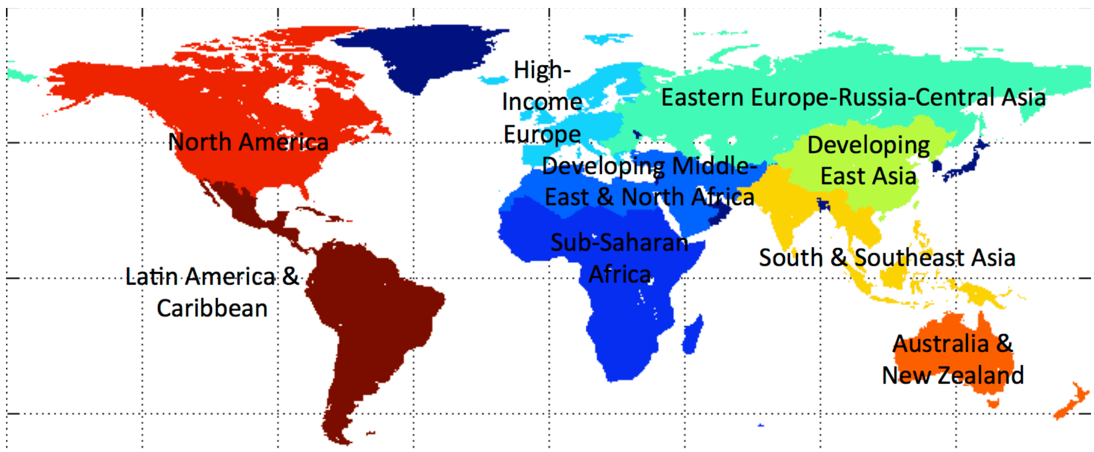

Figure A2: World regions used in the analysis. Dark blue: not included

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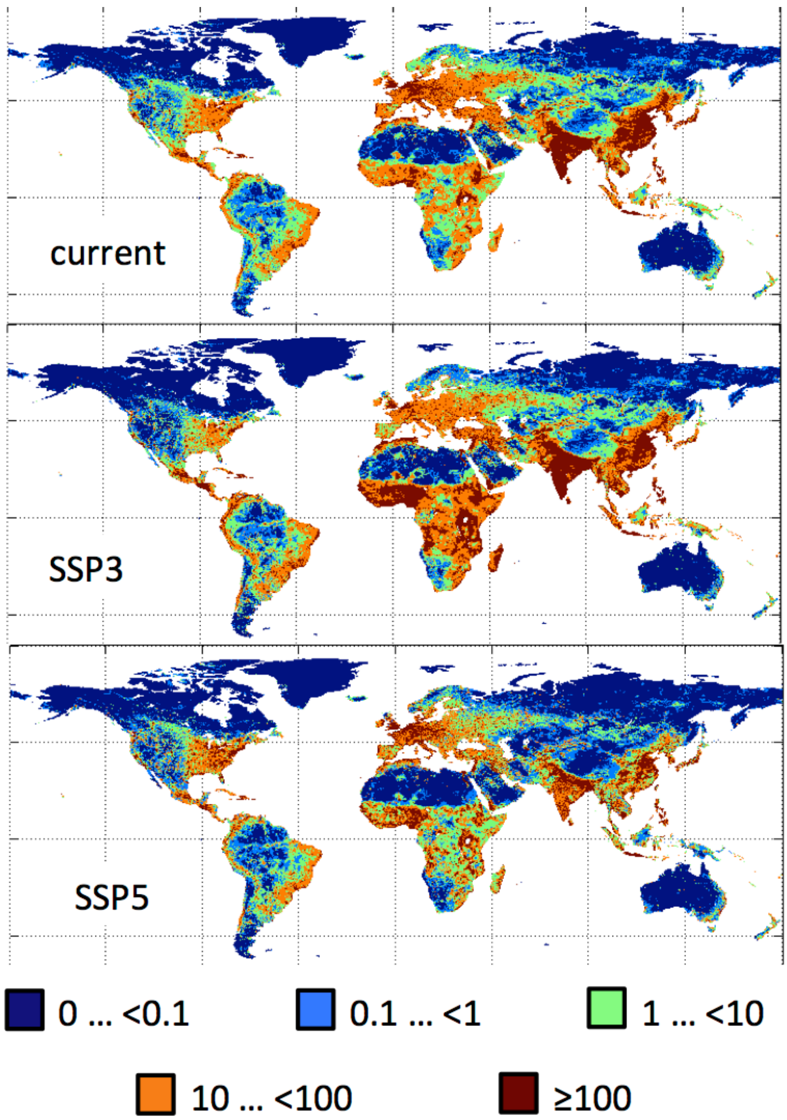

Figure A3: Population density categories for current (2010) and future (2090) conditions for the SSP3 and SSP3 demographic scenarios.

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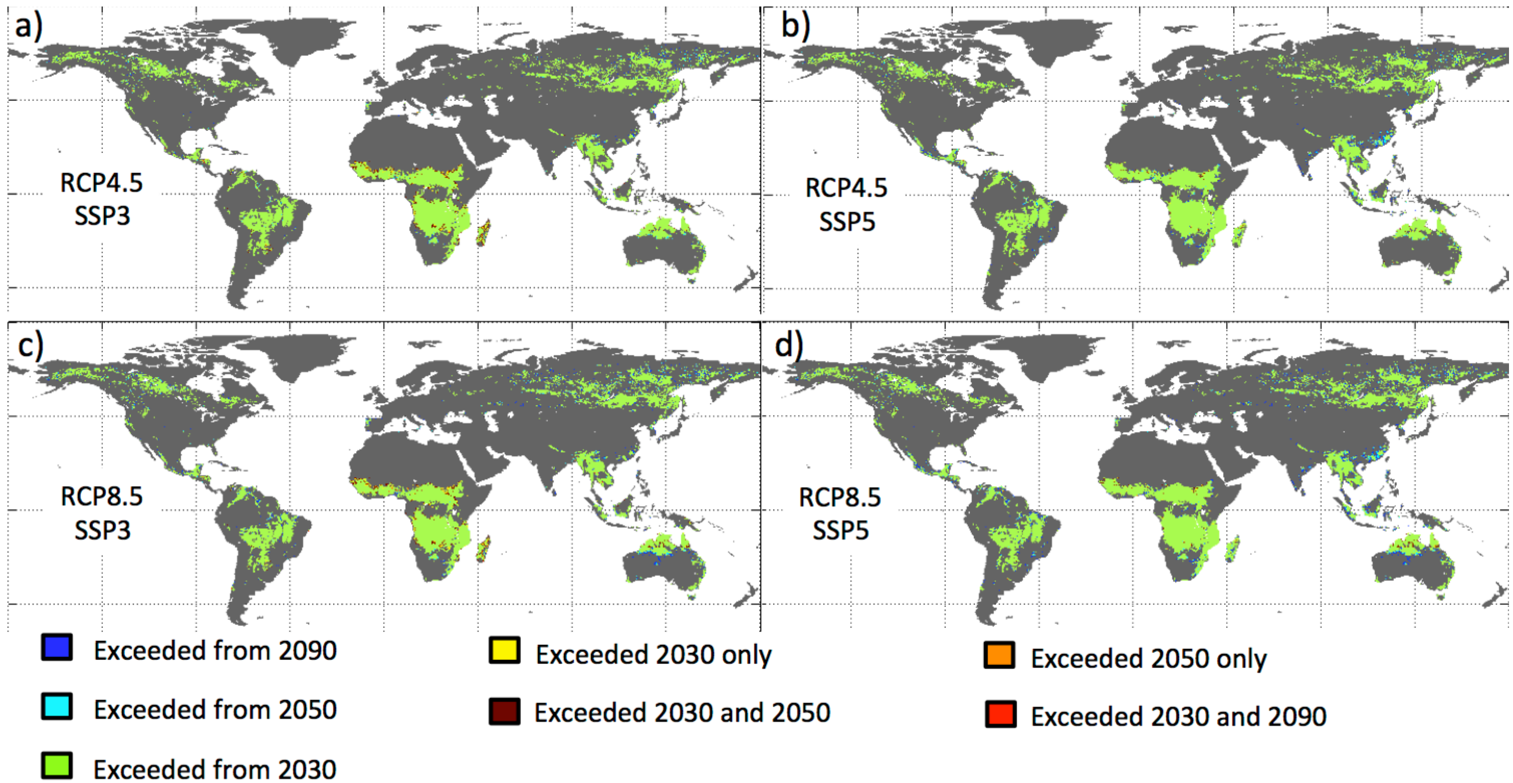

Figure A4: Timing of when annual wildfire emissions exceed 0.2 g PM2.5 m^{-2} yr^{-1} for the time windows 2030, 2050 and 2090a, b) RCP4.5 and c, d) RCP8.5 climate scenario; a, c) SSP3 and b, d) SSP5 demographic scenario.

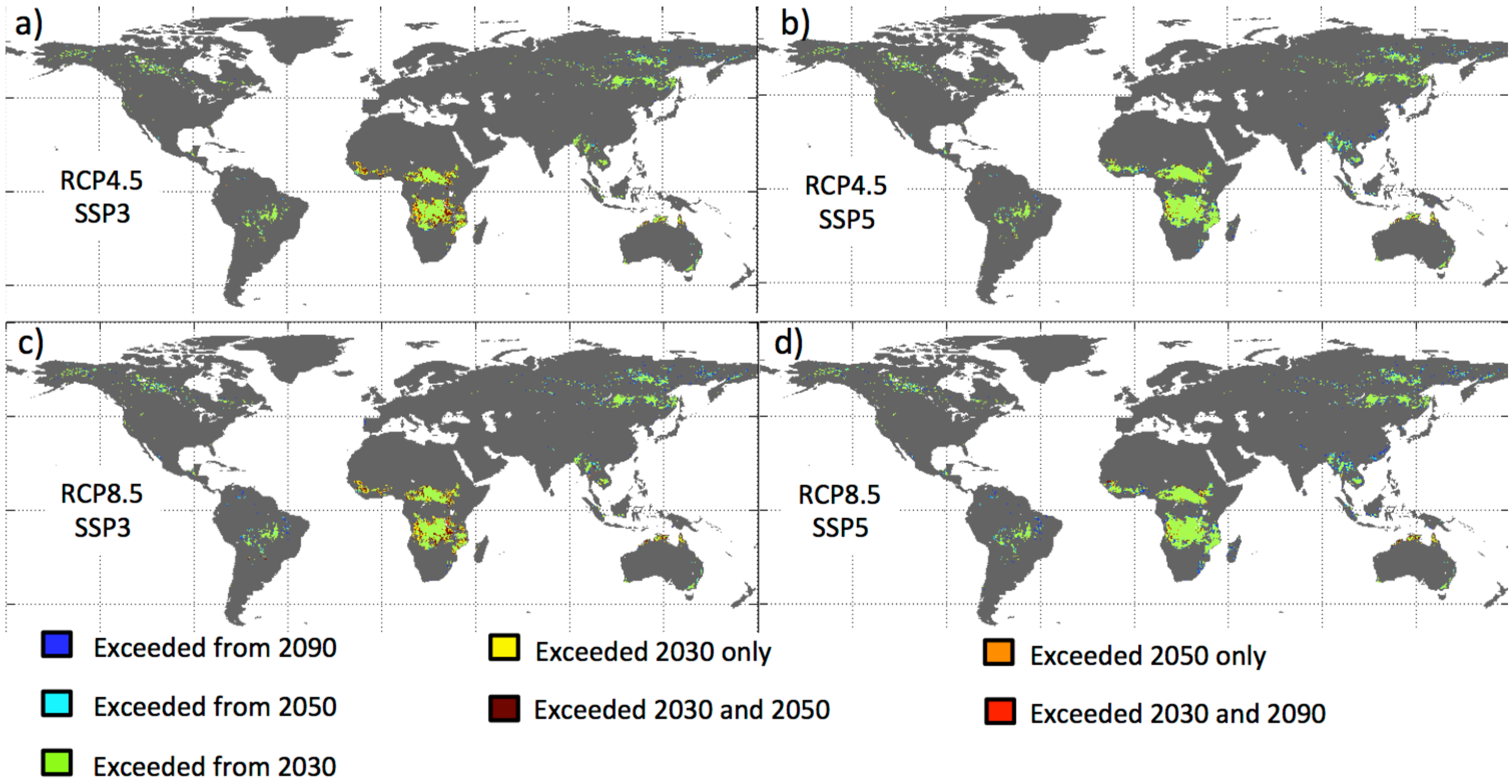

Figure A5: as previous figure, but for a threshold of 1 g PM2.5 m^{-2} yr^{-1}.

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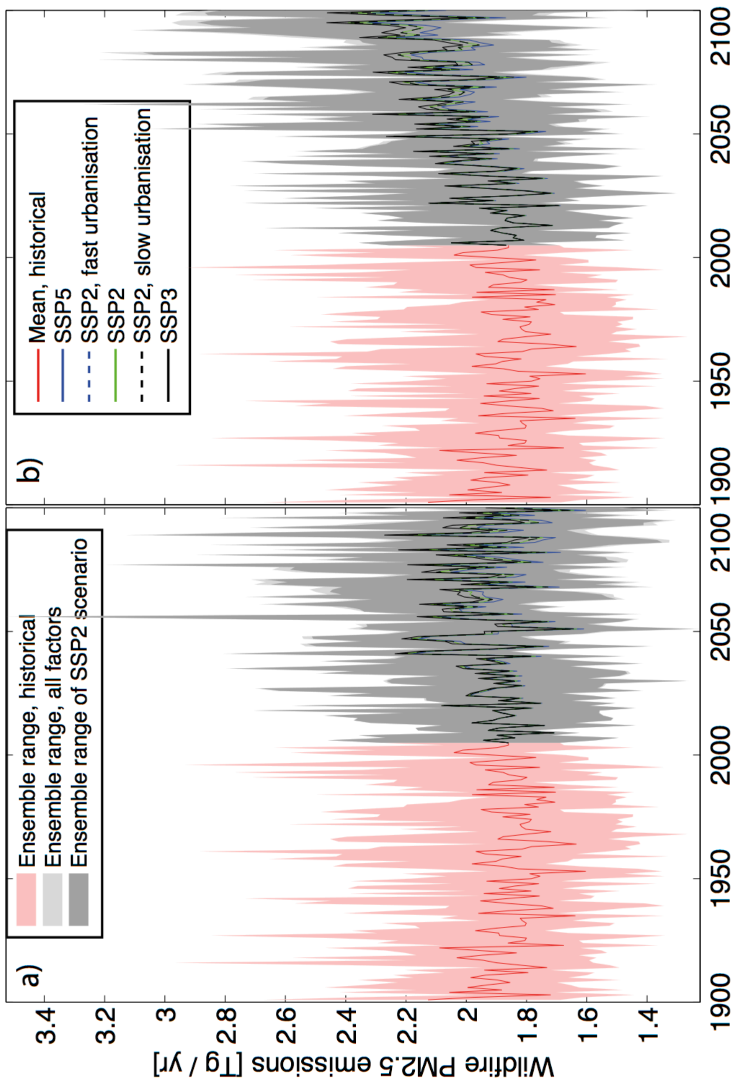

Figure A6: Simulated annual wildfire PM2.5 emissions by LPJ-GUESS-SIMFIRE for the Western U.S. (region USA-W, Table A1).