Climate, CO_2, and demographic impacts on global wildfire emissions
by W. Knorr, L. Jiang, and A. Arneth

The author replies here repeat the Author Comments from the on-line discussion, but add a description of the specific changes applied to the text **(in bold, regular)**

Response to comments by anonymous reviewer #1

1) I suggest the title be changed to "Climate CO2 and human population impacts on global wildfire emissions". Demography can be either vegetation or human, and this wasn't entirely clear given the model being used and that the abstract/introduction discusses 'woody thickening' also as a demographic process.

Reply: We accept that "demographic" is also used in the context of vegetation dynamics - especially for the readership of Biogeoscience - and are grateful for the clarification.

We have changed the title as suggested.

2) Please provide a more mechanistic description of why LPJ-GUESS woody encroachment results in reduced emissions under the CO2 scenario. Is it because of a decrease in fine fuels (i.e., grass), or is it because of the fire resistance of the woody PFT being greater than grasses? It is not clear in the manuscript which process in LPJ-GUESS actually causes the decrease in emissions associated with woody thickening.

From an LPJ-GUESS perspective, what exactly is 'woody thickening' ? Is it an increase in the number of individuals per cohort, i.e., stand density, or an increase in stand biomass, e.g., greater productivity?

Reply: Woody thickening in the context of this study is an increase in the cover fraction of woody vs. herbaceous plant functional types (PFTs). Cover fraction is measured as the fractional leaf area index of each PFT at full leaf development. This measure is closely related to the ratio of the number of woody vs. herbaceous cover on a grid cell, i.e. the total over all patches and cohorts. Because woody plants are on average of higher biomass, it also means an increase in biomass per grid cell, but this is only a consequence of the change in community composition.

As to the first question of how woody thickening leads to decreases in emissions: There are two effects, one on fire spread and one on fuel load. When the fraction of shrubs increases, the area belonging to the biome "shrubland" increases relative to the area of the biome "savannah and grassland". a(B) (Equ. 1 or 3) is an empirical parameter representing fire spread and is 0.889 for savannah and grassland, but 0.470 for shrubland, so that for a given climate, leaf area index and population density, an increase in the fraction of shrubland immediately leads to a decrease in burned area. The second effect results from the fact that in LPJ-GUESS, 100% of live and dead leaves burn in a fire for grasses. In the case of woody vegetation, 100% of dead leaves but only between 46 and 59% of live leaves (depending on mortality), 20% of dead wood and no live wood burn in a fire (Knorr et al. 2012).

The first effect can be seen by a decreasing effect of CO_2 on fire emissions via burned area (Figures 4 and 5 in the manuscript), because increased atmospheric CO_2 favours shrubs over grasses in most regions except the coldest and most arid. The second effect is demonstrated by Figure 1: Woody thickening also leads to a decline in the fraction of NPP that is eventually emitted in fires, which is highest in savannahs and grasslands in general, but markedly declines in Africa and North Australia, where the highest emissions per area occur.

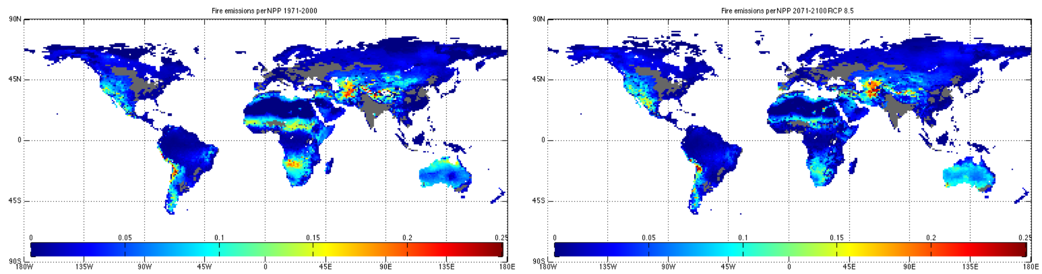

Figure 1: Fire emissions as fraction of NPP. Left: 1971-2000 ensemble average. Right: 2071-2100 RCP8.5 ensemble average.

We have added a brief description of the specific effects of woody thickening (Methods, 3rd paragraph).

3) Much is made of the Bistinas 2014 and Knorr 2014 paper on whether increases in ignitions cause increases in fire frequency. However, this seems at odds with how population density (a proxy for ignitions) is linearly related to burned area. Given that the demography plays such an important role in this paper, can you try clarify these statements in the context of how the model is developed.

Reply: Our argument is that in most of the world today, the fire regime is ignition saturated, decoupling burned area from the number of ignitions. The argument rests no so much on Knorr et al. (2014) and Bistinas et al (2014) as it does on the regional study by Guyette et al. (2002; cited and discussed by Knorr et al. 2014) who demonstrated this effect very clearly in historical data from North America. We believe that the findings by Guyette et al. provide a compelling explanation of why several studies have found an overall negative impact of population density on burned area, not only the ones cited for the global scale, but also Archibald et al. (2008, 2010) and Lehsten et al. (2010) for Africa.

We have removed the sentence "As discussed by Knorr et al.~(2014) and Bistinas et al.~(2014), evidence is lacking whether increases in ignitions actually lead to increased fire frequency on a global scale", and have instead added a discussion of ignition saturation, and a sentence contrasting the more common approach where ignition saturate is not foreseen due to the mathematical representation of burned area: "This approach, based on Venevsky et al. (2002), always leads to an increase in burned are if ignitions increase, all else being equal" (Discussion, end of 3rd last paragraph).

4) *Lightning is also an important cause of fire. Romps et al. (2015 Science) suggest lightning strikes in North America will increase by 50% this century. Some discussion of lightning ignitions, and lightning strike changes with climate seems warranted.*

Reply: Thank you for pointing out this recent publication which we have not been aware of. We expect that in the few areas where the fire regime is still ignition limited (parts of the boreal zone and Australia), an increase in lightning strikes could potentially lead to an increase in emissions (see previous comment on ignition saturated fire regimes). However, the sensitivity experiment where we assumed an ignition limited fire regime below 0.1 inhabitants per km^2 resulted only in very small changes in simulated emissions. Even though this simulation did not account for possible changes in lightning ignitions (but it implicitly assumes a certain constant background ignition in the absence of humans), the small impact it had on simulated emissions makes us believe that the effect of lightning on fire emissions will remain small.

We have added a corresponding statement directly after the text referring to the previous point (Discussion, end of 3rd last paragraph, last sentence) pointing out the possible impact of increasing lightning activity in remote areas and refer to the publication by Romps and co-workers.

5) Minor comments

- P15015 Line 25: I think you mean < 3 mm (not > 3 mm) when describing the Nesterov Index

Reply: Thank you for spotting the error.

Corrected.

6) - Check EMS mix up with ESM throughout manuscript

Reply: Thank you again.

Corrected two instances of the mix-up.

7) - Can you describe how the patches are selected to be burned once the grid cell burned area is estimated

This is a good question, as there are indeed two modes of operation possible with LPJ-GUESS. We have used the stochastic-mortality mode, which means that for woody vegetation each individual in a patch is selected as either killed or surviving with a probability equal to one minus the PFTs fire-related mortality (see Table 1 in Knorr et al. 2012). For grass PFTs, the number of individuals in a patch is not defined (Smith et al. 2001). We do not select whole patches to be killed at random, which is motivated by the large size of a grid cell compared to the burned area of the average fire. This would be different if a simulation was carried out at the single-ecosystem scale, or the number of patches simulated was several orders of magnitude higher.

A clarification has been added to first paragraph of the Methods section before the last sentence.

8) - The relationship between demography and burned area is optimized for present-day observations. However, we know that the fire suppression and management policies change regularly. Additional discussion on the role of management, particularly on whether new policies that might allow large fires to burn, thus changing the burned area/demography relationship, would be useful.

Reply: This is indeed a useful suggestion for the conclusions and outlook, for which we are grateful. While we believe that the main reason why humans suppress fires has to do with the erection of barriers to fire spread rather than direct fire prevention or suppression, we can certainly see a role for changes in fire policy which studies as the present could inform.

We have therefore added the corresponding statement (Conclusions, last paragraph).

9) - Change "Climate effects" -> climate affects

Reply: Thank you.

Corrected (2nd paragraph of Subsection 2.4 "Analytical framework").

Response to comments by anonymous reviewer #2

1) The study of Knorr et al. explores a models sensitivity in fire emissions to cli- mate CO2 and population density for the 20th and 21th century. The study is based on a large number of simulations which differ in their input datasets. This and the differentiation between differnt degrees of urban population represents a substantial novel aspect.

The manuscript is well-structured with an appriate number and high quality of figures. My major concern is the design of the factorial experiment. Stein and Alpert describe a method for factor separation in numerical simulations. They show that the synergies between different factors can be rather large and are important to consider, when quantifying the effect of a variable. The effects of different variables are not simply additive as assumed in eq. 4. The authors here not only negelect the effect of synergies but map them into the effect of fertilization (eq. 6). This procedure can bias the derived effect of CO2. The way the method is presented here is quite complicated. Following more closely the proposed method by Stein and Alpert (1993) could simplify the presentation and analysis and most importantly remove possible biases. See for instance Calvo and Prentice (2015) for a similar application of the method.

Reply: We thank the reviewer for pointing out the method by Stein and Alpert. After careful consideration, we believe that an analogous setup of our study using the said methodology could be approximated by the following combination of time windows from existing transient simulations:

Climate	CO_2	population	time window available from existing simulations?
0	0	0	yes
1	0*	0*	no
0	1*	0*	no
0	0	1*	yes
1	1	0*	no
0	1*	1*	yes
1	1	1	yes
2	1*	1*	yes
1	2*	1	no
1	1	2*	no

2	2	1*	yes
1	2*	2*	no
2	2	2	yes

with the following definitions:

0	1901-1930 time-varying input
1	1971-2000 time-varying input
2	2071-2100 time-varying input
0*	1900 fixed input
1*	2000 fixed input
2*	2100 fixed input

Of the required simulations, the following already exist (number of simulations for different SSP population scenarios in brackets):

- variable climate until 2100; CO_2, population fixed at 2000 values (1x)
- variable climate & CO_2 until 2100; population fixed at 2000 values (1x)
- variable climate, CO_2 and population until 2100 (5x);

and the following would still be required:

- variable climate until 2000; CO_2, population fixed at 1900 values (1x)
- variable climate until 1930; CO_2 at 2000 and population at 1900 values (1x)
- variable climate, CO_2 until 2000; population fixed at 1900 values (1x)
- variable climate, population until 2100; CO_2 fixed at 2000 values (5x)
- variable climate, CO_2 until 2000; population fixed at 2100 values (5x)
- variable climate until 2100; CO_2, population fixed at 2100 values (5x).

This setup would therefore require 18 simulations to be added to the existing 7, per Earth System Model (ESM) and Representative Concentration Pathway (RCP) scenario. Since there are 8 ESMs and 2 RCP scenarios, 288 simulations would have to be performed in addition to the existing 112. Since all require a 1000-year spin-up, the fact that some do not need to be to run until 2100 creates only insubstantial savings in computer time. But apart from a 250% increase in the computational effort, there is one more fundamental problem here that leads us to believe that employing the method by Stein and Alpert needs some substantial additional thought before it can be implemented in the present context:

The problem is that the method lends itself most naturally to time slice experiments, such as those presented by Martin Calvo and Prentice (2015). But all simulations listed above are transient simulations that have not been run to steady state and therefore depend on initial conditions. They are therefore not directly comparable (cf. input variables listed above with and without *). And because of the transient setup, our sensitivities are derived from temporal changes between two periods (Equ. 4), and not from the difference between time-slice experiments each run to steady state.

In fact, a better representation of the setup in our study than Equ. 4 would be the following: we run a simulation with only climate varying and ask what the change in emission is between two time periods each (1901-1930 vs. 1971-2000 and 1971-2000 vs. 2071-2100). Then we add varying CO_2 and ask the question how much the change in emissions between the two time periods is affect in this particular simulation. This change is attributed to the combination of climate and CO_2. Finally, we also include varying population density and attribute the temporal change to the combined climate, CO_2 and population effect. Then we decompose the effects by subtracting the combined climate and CO_2 from the full effect, and the climate from the combined climate and CO_2 effect. Essentially we are asking the question: what is the additional change in emissions between two set time periods when making an additional input variable time variant instead of constant, starting from climate only via climate and CO_2 to the full effect. What we do not consider is a simulation where climate and population are variable, but CO_2 is fixed. The reason for this omission is that we simply do not consider this setup of interest and that we are not aware of any model study that has used it.

We agree that the way Equ. .4-7 are presented could easily be misinterpreted to represent single-factor sensitivity experiments that are assumed to add up the full change. This is not the case, because for one we are dealing with a combination of factorial experiments and time change, and also because we do not perturb the system one by one but sequentially. Nevertheless, we have chosen to fix CO_2 and population in the middle of the transient period in order to minimise the size of the difference between the fixed and the variable input.

In order to make this clearer, we have changed Equ. 4-7 to the following:

$$\boldsymbol{E_{T2} = E_{T1} + \Delta E,} \quad \textbf{(4a)}$$

$$\boldsymbol{E_{T2}{}^{p2} = E_{T1}{}^{p2} + \Delta E^{p2}} \quad \textbf{and} \quad \textbf{(4c)}$$

$$\boldsymbol{E_{T2}{}^{cp2} = E_{T2}{}^{cp2} + \Delta E^{cp2}} \quad \textbf{(4b)}$$

with

$$\boldsymbol{\Delta E = \Delta E_{clim} + \Delta E_{CO2} + \Delta E_{pop}} \;, \quad \textbf{(5a)}$$

$$\boldsymbol{\Delta E^{p2} = \Delta E_{clim} + \Delta E_{CO2}} \quad \textbf{and} \quad \textbf{(5b)}$$

$$\boldsymbol{\Delta E^{cp2} = \Delta E_{clim}} \,. \quad \textbf{(5b)}$$

We have added further text below to clarify that we investigate concrete change scenarios rather than generalisable expressions of model sensitivity to small perturbations and a discussions of the limitations of this approach, citing the work of Stein and Alpert, and issues related to the transient nature of the simulations.

A further note on the method by Stein and Alpert: In our opinion, their method, just as the sequential-perturbation / time change method used here, simply asks a concrete *what if* question based on finite differences: What if input A changes by a given amount, what if input B changes, and what if both change? (And analogous for more than two separately varied input fields.) The interaction term is then simply the change in output when both input variables change minus the sum of the changes when only one input is modified. (Or equivalent for more input variables). Even though the equations presented by Stein and Alpert resemble those of a Taylor expansion (and each term can in fact be expressed as one sub-set of the Taylor series), it is important to note that their exchange term is not the same as the two-dimensional cross term a_{xy} of the Taylor series

$$f(x+\Delta x, y+\Delta y) = f(x, y) + a_x\Delta x + a_y\Delta y + a_{xx}\Delta x^2 + a_{yy}\Delta y^2 + a_{xy}\Delta x\Delta y + \text{higher terms}$$

and for that reason we disagree with the notion that their terms are necessarily easier to interpret than the ones we use. As Stein and Alpert note in their article, a difference field derived from output between two experiments that vary in one input field can be difficult to interpret when the underlying model is non-linear. However, we believe that their method does not solve this issue, but only offers one possible gradual improvement. (Another possibility would for example be to derive additional Taylor expansion coefficients based on finite difference approximations, such as a_{xx}, a_{yy} and a_{xy}.) Given finite resources, we believe that investing them into a larger ESM ensemble has been the better choice than employing the method by Stein and Alpert. Doing this in conjunction with transient simulations could be the subject of a later study, but would probably involve the output from only one or two climate models.

2) Another assumption that has the potential to change the explored trends is the crop mask. Regions with high changes in crop cover often show strong changes in fire, these regions are masked in the present study although at least on the regional scale these gridcells might strongly contribute to the trends. See for instance Andela et al. (2014) for the importance of cropland cover increase on trends in Africa. Also a number of studies on cropland abandonment exist.

Reply: We have deliberately chosen to keep the crop mask constant because we wanted to avoid accounting for the direct effect of wildland being replaced by cropland. This would have either required the inclusion of a model for agricultural burning, which we do not have, or would constitute a trivial effect when – as here – we only consider wildfires, because they cannot occur on croplands solely by definition. However, we believe that the main effect of cropland expansion is not limited to suppressing wildfires on croplands, but also due to the infrastructure they tend to be accompanied by, which creates numerous barriers to fire spread. This is discussed extensively and demonstrated on the basis of historical tree ring data by Guyette et al. (2002), and also noted by Andela and van der Werf (2014; 3rd line on page 793):

"This rapid initial decline [of burned area as a function of cropland extent] suggests that agricultural activity does not affect burned area only in the land that is actually converted, but also in the remaining savannas. [...,] large uncontrolled fires are less likely to occur owing to changes in fire management and lower fuel continuity due to, for example, more developed road networks (Shaffer 2010)".

We have added a note at the end of the first paragraph of Subsection 2.4 ("Analytical Framework") that we only consider the indirect effect of crop expansion, not the displacement of wildland by cropland, together with a reference to Andela and van der Werf (2014).

As far as the effect of land abandonment is concerned (not only cropland abandonment), the study by Moreira et al. (2011) points out that at least in southern Europe, this phenomenon has generally increased flammability of the landscape. This is the reverse of the effect simulated for Africa, but plays a role in Europe where the SSP3 scenario predicts a substantial population decline. These effects are included through the empirically derived shape of the burned-area vs. population density relationship (Equ. 1).

3) The effect of CO2 fertilization has been adressed by some previous studies that should be mentioned and discussed (for instance Calvo and Prentice, 2015, Lasslop and Kloster, 2015, Kelley and Harrison, 2014).

Thank you for pointing out these studies. We have added a discussion of the results by Kelley and Harrison (2014) to the last paragraph but one of Section 4 (formerly last paragraph), where we discuss the characteristic zonal structure of our results found for Australia under 21st century climate warming.

We have also added references to the work by Lasslop and Kloster (2015), who report a 20% increase of burned area and 40% increase of emissions due to the CO_2 fertilisation effect during the 20th century (3rd paragraph of Section 4). Our result contrasts with Lasslop and Kloster's, with a small decrease in burned area and close to no effect on emissions for the present study.

We have also added a reference to Martin Calvo and Prentice (2014) to the introduction section where we describe the different simulated effects of climate, CO_2 and vegetation distribution (3rd paragraph of Section 1). We have added a sentence that discusses the importance of interactions between climate, CO_2 and vegetation dynamics, a main finding of the cited work. We have not added a discussion of their work to Section 4 because of the different time scales concerned (glacial-Holocene change vs. 21st century climate change).

4) Technical Comments

p.1502, l. 10: also here synergies are neglected, moreover, can only fuel change or could it also be the fuel combustion completeness.

Reply: See the reply to this reviewer's Comment 1 on the merits of the Stein and Alpert method. In this case, we express the change in emissions due to burned area change in a first-order forward computation using the previous time slice's ratio between emissions and burned area and the change in burned area attributed to CO_2 change derived from a sequential / transitional simulation setup. Synergy terms are not neglected, but do not appear in this configuration. However, we agree that it is important to point out that we summarize all of the remaining emission change due to CO_2 to the fuel effect, including effects that differ from the first-order forward calculation. This calculation therefore only serves as a first approximation for separating these factors.

We have edited text just before Equ. 8 (now 6) to better explain the approach used to distinguish fuel load from burned area effects.

As for the question of fuel load vs. combustion completeness, the reviewer rightly points at an inconsistency in the formulation: emissions change due to either changes in burned area, or changes in the amount of fuel combusted per area – see for example Figure 6, where this quantity is called "combustible fuel load". By contrast, the text referred to mentions emission changes via changes in "fuel load".

We have modified $\Delta E_{CO2}^{f.l.}$ to $\Delta E_{CO2}^{c.f.l.}$ in the text.

5) p.1502, l. 17: in order "to"

Reply: **Thank you, corrected.**

6) p. 15029, l. 15: there are also some studies indicating an increase at least at the end of the 20th century that are worth mentioning, for instance Mouillot and Field (2005).

Reply: A comprehensive discussion of the issue of historical changes of fire emissions can be found in van der Werf et al. (2013), which mentions the study by Mouillot and Field (2005) – a historical reconstruction – but also discusses various arguments based on ice core proxies.

We have added a caveat with a reference to van der Werf et al. (2013).

7) p. 15030 l.23: a large part of savannas are used as pasture and fire is used as a tool to avoid woody encroachment. pasture areas may most likely be maintained as grasslands and therefore woody encroachment could actually lead to an increased use of fire to maintain the pastures. Is your model applicable to such systems over such time scales where strong changes in human land use can be expected? As far as I understand the only way you consider land use is by masking cropland areas?

Reply: SIMFIRE has been trained on actual observations of burned area that reflect the effect of land use. These effects are subsumed under the effect of population density. The model by Bistinas et al. (2014) also considers cropland and grazing land as statistical contributing factors for predicting burned area. However, we do not believe that existing scenarios of these factors in conjunction with population density are of sufficient quality yet to be included in these simulations.

Since our simulations are based on a model trained on recent data, we implicitly assume that management practices do not adapt themselves to woody encroachment. However, Wigley et al. (2010) report a strong and rather universal increase in woody vegetation cover based on aerial photography from South Africa between the 1930s and the early 2000s. The increase also happens in lands managed for grazing, despite of the well-known efforts of herders to decrease shrub cover. Furthermore, grazing might even lead to decreased shrub cover, contrary to the efforts of herders, because of over-grazing (Bond and Midgley 2012). There is also evidence for woody thickening over large scales in Australia based on a 27-year long satellite record (Donohue et al. 2009). These observations support our modeling results and we therefore believe that the effects of management tend to be insufficient to counteract a general trend towards woody thickening and that the assumption of temporally invariant management is therefore a reasonable approximation.

We have added an additional discussion of these points (last paragraph of Section 4) and a reference to Wigley et al. (2010) in addition to Buitenwerf et al. (2012) when introducing woody thickening (Section 1, 3rd paragraph).

8) p. 15032, l. 25: fire frequency in terms of burned area?

Reply: Yes. Sometimes "fire frequency" is indeed used as number of fires per time interval, but here it refers to burned area.

We have replaced "fire frequency" by "burned area" throughout the text to avoid any misinterpretation.

Remaining changes

The numbering for the logarithmic colour bars in Figs. 4 and 5 has been corrected.

Corrected $\Delta E_{CO2}{}^{a.b.}$ and changed to $\Delta E_{CO2}{}^{b.a..}$ (before Equ. 8, now 6).

Newly added references: Andela and van der Werf (2014), Claussen et al. (2001), Guyette et al. (2002), Martin Calvo and Prentice (2015), Romps et al. (2014), Stein and Alpert (1993), van der Werf et al. (2013), Venevsky et al. (2002).

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Title:

Climate, CO_2, and human population impacts on global wildfire emissions

Wolfgang Knorr 7/12/2015 14:01
Deleted: demographic

Authors:

W. Knorr*[1], L. Jiang & A. Arneth[3]

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

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

[3]KIT/IMK-IFU, Garmisch-Partenkirchen, Germany

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

Abstract:

Wildfires are by far the largest contributor to global biomass burning and constitute a large global source of atmospheric traces gases and aerosols. Such emissions have a considerable impact on air quality and constitute a major health hazard. Biomass burning also influences the radiative balance of the atmosphere and is thus not only of societal, but also of significant scientific interest. There is a common perception that climate change will lead to an increase in emissions as hot and dry weather events that promote wildfire will become more common. However, even though a few studies have found that the inclusion of CO_2 fertilization of photosynthesis and changes in human population patterns will tend to somewhat lower predictions of future wildfire emissions, no such study has included full ensemble ranges of both climate predictions and population projections, including the effect of different degrees of urbanisation.

Here, we present a series of 124 simulations with the LPJ-GUESS-SIMFIRE global dynamic vegetation – wildfire model, including a semi-empirical formulation for the prediction of burned area based on fire weather, fuel continuity and human population density. The simulations comprise Climate Model Intercomparison Project 5 (CMIP5) climate predictions from eight Earth System Models using two Representative Concentration Pathways and five scenarios of future human population density based on the series of Shared Socioeconomic Pathways (SSPs), sensitivity tests for the effect of climate and CO_2, as well as a sensitivity analysis using two alternative parameterisations of the semi-empirical burned-area model. Contrary to previous work, we find no clear future trend of global wildfire emissions for the moderate emissions and climate change scenario based on the Representative Concentration Pathway (RCP) 4.5. Only historical population change introduces a decline by around 15% since 1900. Future emissions could either increase for low population growth and fast urbanisation, or continue to decline for high population growth and slow urbanisation. Only for high future climate change (RCP8.5), wildfire emissions start to rise again after ca. 2020 but are unlikely to reach the levels of 1900 by the end of the 21st century. We find that climate warming will generally increase the risk of fire, but that this is only one of several equally important factors driving future levels of wildfire emissions, which include population change, CO_2 fertilisation causing woody thickening, increased productivity and fuel load, and faster litter turnover in a warmer climate.

1 Introduction

Wildfires are responsible for approximately 70% of the global biomass burned annually (van der Werf et al. 2010, updated). Emissions from wildfires in the form of trace gases and aerosols can have a considerable impact on the radiative balance of the atmosphere (Langmann et al. 2009) and also constitute a large source of atmospheric pollutants (Kasischke and Penner 2004). At the same time, wildland fires are an important component of terrestrial ecosystems (Bowman et al. 2009) and the Earth system in (Arneth et al. 2010). Fires respond to changes in climate, vegetation composition and human activities (Krawchuk et al. 2009, Pechony and Shindell 2010, Kloster et al. 2012, Moritz et al. 2012), with some model simulations showing a positive impact of climate change on emissions during the 21st century, but a negative, albeit smaller, impact due to changes in land use and increased fire suppression (Kloster et al. 2012).

Empirical studies designed at isolating the effect of human population density – here used as an aggregate value representing human interference at the landscape scale – have generally shown that higher population density *per se* leads to a decrease in the annual area burned (Archibald et al. 2008; Knorr et al. 2014; Bistinas et al. 2014), even though there is a common perception that wildfire activity peaks at intermediate levels of population density. This apparent paradox was shown to be the result of co-variations between population density and other factors such as fuel load or flammability - if these co-variations are taken into account, the view of a negative impact is consistent with the observed peak (Bistinas et al. 2014).

The main future drivers of changing wildfire have potentially opposing effects on emissions – temperature (increasing), CO_2 via productivity (increasing), CO_2 via woody thickening (Wigley et al., 2010; Buitenwerf et al. 2012; decreasing), and human population density (decreasing emissions). In the meantime, socio-demographic change, interacting with other economic and technological factors, may also lead to climate change – e.g. slow population growth combined with a conventional development pathway of high fossil fuel dependence would result in high CO_2 emissions and large temperature increases. Moreover, the same population growth but with different urbanization trends could also lead to different levels of spatial population distributions and concentrations, and consequently different results concerning wildfire emissions. Therefore, it is important to first assess the impact of each factor individually before arriving at conclusions concerning aggregate effects. Another important point of consideration is that if climate forcing is based on a model with low climate sensitivity to CO_2 change (i.e. relatively small change in global mean temperature simulated for a given rise in atmospheric CO_2), CO_2 effects might dominate over climate effects. The reverse applies to climate models with a high climate sensitivity. We therefore use an ensemble of climate models instead of only one or two, consider a wide range of future scenarios of population density change, and differentiate between the effects of changes in not only population sizes within a country, but also population spatial distribution via urbanisation.

While previous studies have focused on the task of predicting future wildfire emissions and have at most considered impacts of population changes separately to those of climate and CO_2, here we partition the projected changes into the following drivers: climate via changes in burned area, climate via changes in fuel load, CO_2 via changes in burned area, CO_2 via changes in fuel load, and population density considering both the effects of population growth and urbanisation. The goal is a better understanding of the underlying processes of wildfire emission changes, which should help establishing the necessary links between climate policy (emissions), climate science (climate sensitivity), demography, air pollution and atmospheric chemistry, as well as wildfire management.

2 Methods

2.1 Models and driving data

We use the coupled fire-vegetation model LPJ-GUESS-SIMFIRE (Knorr et al. 2014; Knorr et al. submitted) to simulate establishment, growth and mortality of natural vegetation, fuel load, burned area and wildfire emissions under changing climate, CO_2 and human population density. LPJ-GUESS (Smith et al. 2001) is a global dynamic vegetation model that simulates potential vegetation as a mixture of user-defined plant functional types (PFTs) which compete with each other in so-called patches. Each PFT is characterized by a set of traits, such as leaf longevity and phenology, growth form and bioclimatic limits to establishment and survival. In these simulations, we use five patches per grid cell, and within each patch, LPJ-GUESS simulates several age cohorts. In "cohort mode", which is used here, all individuals of a cohort are assumed to have identical characteristics. When a fire occurs, individuals of woody PFTs within each patch a selected at random to be killed or to survive according to the PFT's fire resistance (Knorr et al.\~2012). Grass PFTs have no individuals and therefore we only adjust the biomass of each these PFTs. We use PFTs designed for global simulations as given by Ahlström et al. (2012).

Fire impacts on vegetation are simulated at monthly intervals as described by Knorr et al. (2012). SIMFIRE predicts annual fractional burned area, A (the fraction of each grid cell burned per year) using the following equation:

$$A(y) = a(B)\, F^{b}\, N_{max}(y)^{c} \exp(-ep) \qquad (1)$$

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Here, y is the fire year defined as in Knorr et al. (2012) in such a way that it never "cuts" the fire season into two, B the biome type, F is annual potential fraction of absorbed photosynthetically active radiation (FAPAR), an approximation of vegetation fractional cover easily observed from satellites and here used as a measure of fuel continuity (Knorr et al. 2014), N_{max} is the annual maximum Nesterov Index based on daily diurnal temperature mean, T_m, range, T_r, and precipitation, P, and p is human population density. The Nesterov index used is given by Thonicke et al. (2010) as the cumulative sum of T_m*(T_r + 4K) over all consecutive days with equal or less than 3 mm rainfall. $a(B)$, b, c, and e are global parameters derived by optimisation of SIMFIRE burned area against observed burned area from GFED3 (Giglio et al. 2010) on a spatial grid and for the entire globe (Table 2, "GFED3", "All population densities" of Knorr et al. 2014). To derive monthly burned area, we use the average diurnal cycle of burned area derived from GFED3 for 2001-2010 using a variable spatial averaging radius around each grid cell which is at least 250km but has a total burned area over the period of 10,000km^2. Information on biome type is passed from LPJ-GUESS to SIMFIRE, where biome type is a discrete number ranging from one to eight, using FAPAR of woody and herbaceous vegetation and of vegetation of at least 2m as well as geographic latitude as information. F in Eq. (1) is a bias corrected value derived from LPJ-GUESS simulated FAPAR, F_s, via:

$$F = 0.42\, F_s - 0.15\, F_s^2 \qquad (2)$$

In LPJ-GUESS, woody thickening effects emissions in two ways: When the fraction of shrubs increases, the area belonging to the biome ``shrubland" increases relative to the area of the biome ``savannah and grassland". Because $a(B)$ of Eq.~(1) for the former is approximately half of the value for the latter (Knorr et al.\~2014), an increase in the fraction of shrubland immediately leads to a decrease in burned area.

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The second effect results from the fact that in a fire, 100\% of live and dead leaves of grasses burn, while for woody vegetation, 100\% of dead leaves but only between 46 and 59\% of live leaves (depending on fire resistance), 20\% of dead wood and no live wood burn in a fire (Knorr et al.\~2012). As a result, the fraction of net primary productivity emitted in a fire tends to decrease with woody encroachment. The measure used to document woody thickening in LPJ-GUESS is the maximum seasonal leaf area index (LAI) assigned the woody individuals of a grid cell divided by the total grid cell LAI.

LPJ-GUESS-SIMFIRE, in the following denoted "LPJ-GUESS", is driven by output from Earth system model (ESM) simulations from the CMIP5 project (Taylor et al. 2012) in a way mostly following Ahlström et al. (2012), where climate output of monthly mean temperature, precipitation and downward shortwave radiation is bias corrected using the mean observed climate for the period 1961-1990, and atmospheric CO_2 levels used by LPJ-GUESS are taken from the RCP scenarios as prescribed for CMIP5 (Meinshausen et al. 2011). In variance to the cited work, we use CRU TS3.10 (Harris et al. 2014) as climate observations, and we predict monthly mean diurnal temperature range and number of wet days per month based on linear regressions against mean temperature and precipitation, respectively. Simulations are carried out on an equal-area pseudo-1° grid, which has a grid spacing of 1°x1° at the equator and a wider E-W spacing towards the poles in order to conserve the average grid cell area per latitude band.

We use global historical gridded values of human population density from HYDE (Klein-Goldewijk et al. 2010) for simulations up to 2005. For future scenarios, no gridded data are available, but we use instead per-country values of total population and percentage of urban population. In order to generate gridded population density after 2005, we use separate urban and rural population density from HYDE for the year 2005 and re-scale both by the relative growth of each in each country. After this procedure, we multiply the population density of all grid cells representing each country by a constant factor such that the growth of the total population of the given country relative to the 2005 HYDE data matches that of the per-country total population scenario used.

2.2 Scenarios

We run simulations for two climate change scenarios from the Representative Concentration Pathways (RCP). Of these, RCP4.5 represents an approximate radiative forcing scenario typical of the majority of stabilization scenarios included in the Fourth Assessment of Report of the International Panel on Climate Change. The other, RCP8.5, is a typical case of high emissions resulting from a lack of enforced stabilization of greenhouse gases, leading to high levels of climate change (van Vuuren et al. 2011). In this study, we will consider both scenarios separately as two alternative futures without any assignment of relative probabilities.

Climatic trends simulated for the 20th century as well as for RCP4.5 and RCP8.5 are shown in Table 1 for different regions, for the eight-ESM ensemble mean and range. (For definition of regions see Section 2.4 and Fig. 4.) There is a spatially rather uniform warming trend of around half a °C during the 20th century roughly in accordance with observations (Harris et al. 2014), with inter-model differences larger than differences between regions. Precipitation declines slightly during the same period, most strongly for already dry Middle East, with generally rather large inter-model differences, in particular for Africa, Oceania and South Asia. Temperature change under the RCP4.5 scenario towards the end of the 21st century is around

+2.5°C for most regions, except for higher values for the two regions comprising most of the Arctic (North America, North Asia), while precipitation overall increases, albeit with considerable declines for Oceania and Middle East on average, and for South America and Africa for the their respective ensemble minima. For RCP8.5, global mean temperature change reaches as high as +5°C, with North America, North Asia and Middle East exceeding this value. Precipitation changes are similar to RCP4.5, but with both the inter-model ranges and the inter-region differences considerably amplified. (For example, there is an almost 40% decline for Oceania for the ensemble minimum.)

For population scenarios, we use marker scenarios of the Shared Socioeconomic Pathways (SSPs; O'Neill et al. 2012, Jiang 2014). Following Knorr et al. (submitted), we consider a total of five scenarios: SSP2 scenario with medium population growth and central urbanisation, two extreme scenarios with either high population growth and slow urbanisation (SSP3) or low population growth with fast urbanisation (SSP5), and two further scenarios in which the medium population growth (SSP2) is combined with either slow (SSP3) or fast (SSP5) urbanisation. Fur the purpose of analysis, we will consider these five scenarios equally plausible, keeping in mind, however, that this is mainly a working hypothesis.

2.3 Simulations

We combine output from eight ESMs with two different emissions pathways, one based on RCP4.5 and one on RCP8.5, all run with the medium population and central urbanisation scenario of SSP2. These 16 simulations are repeated six times using the other four population and urbanisation scenarios, one simulation each where population is held constant at 2000 levels, and one simulation where both population and atmospheric CO_2 levels are held constant at 2000 levels, giving 8 * 2 * 7 = 112

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simulations. To these we add two more sets of six simulations each with a different parameterisation of SIMFIRE, comprising runs using the SSP2 demographic scenario, fixed population, and fixed population and CO_2 and output from MPI-ESM-LR based on either RCP4.5 or RCP8.5. The first alternative SIMFIRE parameterisation is derived from a global optimisation against MCD45 burned area (Roy et al. 2008) according to Knorr et al. (2014, Table 2, "MCD45", "All population densities"), and the other assumes a slight increase in burned area with increasing population density if p is less than 0.1 inhabitants per km^2, where Eq. (1) is replaced by:

$$A(y) = (0.81 + 1.9p)\, a(B)\, F^b\, N_{max}(y)^c \exp(-ep), \qquad (3)$$

based on results presented by Knorr et al. (2014).

2.4 Analytical Framework

Since the present analysis only considers wildfires, we exclude all grid cells that contain more than 50% of cropland at any time during 1901-2100 in either the RCP6.0 or 8.5 land use scenarios (Hurtt et al. 2011). The threshold of 50% is the same as used during SIMFIRE optimisation. A time-invariant crop mask is used in order to avoid introducing time trends in the results through temporal variations of the crop mask. We therefore only consider the indirect of effect of cropland expansion via the empirically derived burned area--population density relationship of SIMFIRE, not the direct displacement of wildlands. This indirect effect can be considerable and arises from the fact that cropland expansion tends to be accompanied by higher population density, a denser road network, and a decrease in burned area in the areas that have not been converted to croplands (Andela and van der Werf 2014).

The changes in emissions may be caused by climate change alone, by changes in atmospheric CO_2, or by changes in population density. Emissions are determined by the product of burned area, the amount of fuel present, and the fraction of fuel combusted in a fire. Climate affects burned area directly by changing fire risk via N_{max}, while climate and CO_2 effect burned area indirectly by changing the vegetation type, which affects *a(B)*, or vegetation cover, which affects *F* in Eq. (1). Fuel load is also affected by vegetation productivity which is driven by both climate and CO_2, and by litter decay rates, which depend on temperature and precipitation (Smith et al. 2001). The combusted fraction of fuel mainly depends on the presence of grasses vs. trees (Knorr et al. 2012). Finally, population density affects emissions through burned area via Eq. (1).

In order to assess the effect of different driving factors on changing emissions, we employ the following analytical framework:

$$E_{T2} = E_{T1} + \Delta E, \quad (4a)$$

$$E_{T2}^{p2} = E_{T1}^{p2} + \Delta E^{p2}, \quad (4c)$$

$$E_{T2}^{cp2} = E_{T2}^{cp2} + \Delta E^{cp2} \quad (4b)$$

with

$$\Delta E = \Delta E_{clim} + \Delta E_{CO2} + \Delta E_{pop} , \quad (5a)$$

$$\Delta E^{p2} = \Delta E_{clim} + \Delta E_{CO2}, \quad (5b)$$

$$\Delta E^{cp2} = \Delta E_{clim} . \quad (5b)$$

where subscript *T1* denotes the temporal average over the initial reference period (either 1901-1930 or 1971-2000), and *T2* over the subsequent reference period (1971-2000 or 2071-2100), *E* are wildfire emissions, ΔE the change in the temporal average of emissions between the two reference periods, and the subscripts "clim", "CO_2" and "pop" denote the effects of changing climate, CO_2 and human population density. The superscripts *p2* are for the simulations with population density fixed at year 2000

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levels, and *cp2* for the simulations with both CO_2 and population fixed at 2000 levels. We chose the year 2000 as a reference year for fixed input variables in the middle of the simulation period in order to minimise deviations from the values of the transient runs.

The climate effect in the context of this study is therefore defined as the change in emissions between two time periods of a transient simulation with variable climate but fixed population density and atmospheric CO_2, the CO_2 effect as the additional change in emissions when CO_2 is also varied in time, and the population effect as the additional effect when population density also becomes time variant. The computed effects are not expressions of model sensitivity to small perturbations, but rather arise from a series of specific scenarios. We choose this order of scenarios for historical reasons: we first include the effect studied most (e.g. Krawchuk et al., 2009; Moritz et al., 2012), then the effect that is usually included as soon as a dynamic vegetation model is used (Scholze et al. 2006), and at last the effect that is the focus of the current study. If we were to add the population effect first -- by including simulations where population changes in time but CO_2 is kept constant -- the results would be somewhat different, and the difference could be expressed as interaction terms following Stein and Alpert (1993). However, this method is usually applied to time slice experiments (e.g. Claussen et al. 2001; Martin Calvo and Prentice 2015) and its application to transient simulations is less straightforward, still depends on a finite perturbations, and would require a large number of additional simulations, which is why we here restricted ourselves to the setup described by Eqs.~(4) and (5).

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Fire emissions here are computed as the product of burned area and area-specific fuel combustion. Therefore, we can further subdivide the CO_2 effect on emissions between those that work via changing burned area ($\Delta E_{CO2}{}^{b.a.}$) and those via changing fuel load as the remainder ($\Delta E_{CO2}^{c.f.l.} = \Delta E_{CO2} - \Delta E_{CO2}^{b.a.}$). We derive the former in a first-order forward projection using emissions per area burned of the previous time step:

$$\Delta E_{CO2}^{b.a.} = \Delta B_{CO2} \left(E_{T1} / B_{T1}\right) , \qquad (6)$$

where B_{T1} is the temporal average of burned area during reference period *T1*, and ΔB_{CO2} the change in burned area due to CO_2 changes, which we approximate in an analogous way to ΔE_{CO2} as:

$$\Delta B_{CO2} = B_{T2}^{p2} - B_{T1}^{p2} - \left(B_{T2}^{cp2} - B_{T1}^{cp2}\right) . \qquad (7)$$

An analogous formulation is used in order to discern climate impacts due to burned area from those due to changes in fuel load and its degree of combustion:

$$\Delta E_{clim}^{b.a.} = \Delta B_{clim} \left(E_{T1} / B_{T1}\right) , \qquad (8)$$

with

$$\Delta B_{clim} = B_{T2}^{cp2} - B_{T1}^{cp2} . \qquad (9)$$

We analyse the main driving factors of emissions changes using Eq. 5–9 for selected large regions, aggregated from the standard GFED regions (Giglio et al. 2010):

1. North America (GFED Boreal and Temperate North America, Central America)
2. South America (GFED Northern and Southern-Hemisphere South America)
3. Europe (same as GFED)
4. Middle East (same as GFED)
5. Africa (GFED Northern and Southern-Hemisphere Africa)
6. North Asia (GFED Boreal and Central Asia)
7. South Asia (GFED South-East and Equatorial Asia)
8. Oceania (GFED Australia and New Zealand)

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For a probabilistic analysis of changes in emissions, we follow previous work by Scholze et al. (2006), who counted ensemble members driven by differing climate models where the change of the temporal average between two reference periods was more than one standard deviation of the interannual variability of the first reference period. The authors found a general pattern of increasing factional burned area in arid regions, and a decline at high latitudes and some tropical regions. Here, we apply the method to emissions and use two standard deviations instead in order to ensure that the change is highly significant.

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3 Results

3.1 Global emission trends

Global simulated emissions taking into account changes in all factors, climate, CO_2 and population, decline continuously between about 1930 and 2020 for all members of the ESM ensemble (Fig. 1). Thereafter, emissions approximately stabilize, albeit with a very slight upward trend during 2080-2100 for the moderate greenhouse gas concentrations and climate change scenario RCP4.5 and the central demographic scenario (Fig. 1a). However, different demographic scenarios lead to considerable variations in simulated emissions: while emissions continue to decline until 2100 under high population growth and slow urbanisation (SSP3), the trend of declining emissions is reversed from around 2010 and the total will resume current levels by the end of the 21^{st} century under low population growth and fast urbanisation (SSP5) when taking the ESM ensemble mean. In general, higher population growth drives emissions downward (comparing SSP3 to SSP5), while faster urbanisation contributes to higher wildfire emissions (comparing SSP2 population with fast and slow urbanisation). By the end of the century, different demographic trends generate approximate 0.2 GtC per year difference (ranging from around 1.1 to 1.3 GtC/yr) under the moderator climate change RCP4.5. Overall, the range of future emissions spanned by the eight ESMs, but using a single, central population scenario, is less than half of the range spanned by all ESMs and population scenarios combined. None of the simulations has late 21st century emissions reach again the levels present at the beginning of the 20th century (Table 2). Only 9 out of 40 simulations show global average emissions during 2071-2100 higher than during 1971-2000, seven out of which are for low population growth and fast urbanisation, and one for intermediate population growth and fast urbanisation.

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Under RCP 8.5, with high greenhouse gas concentrations and climate change, global wildfire emissions start to rise again after 2020 even for the central demographic scenarios (SSP2) and by the end of the 21st century reach levels only slightly below those of the beginning of the 20th century (Fig. 1b). According to this climate change scenario, the world is currently in a temporary minimum of wildfire emissions, independent of demographic scenario or ESM simulation. The population scenario rather determines when emissions are predicted to rise again and how fast emissions increase. For a scenario of high population growth and slow urbanisation (SSP3), emissions rise again after ca. 2070 and reach about 1.2 GtC/yr by the end of the century, while under the fast urbanisation scenarios (SSP5 and SSP2 population with fast urbanisation), they already start rising around 2020. Under RCP8.5, different demographic trends result in different wildfire emissions ranging from 1.2 to 1.5 GtC/yr. Overall, for 28 out of 40 simulations average emissions during 2071-2100 are higher than during 1971-2000, and for three out of the eight simulations with low population growth and fast urbanisation they are even higher than for 1901-1930 (Table 2).

Simulations with atmospheric CO_2 and population held constant at 2000 levels reveal the impact of climate change on simulated wildfire emissions (Fig. 2a). The climate impact is here shown as the difference in emissions against the average during 1971-2000 (1.28 PgC/yr, see Table 2). There is a modest positive climate impact on global emissions for RCP8.5, which reaches close to 10% towards the end of the 21st century for the ESM ensemble mean, with a range between close to 0 and +20%. For the past, there is no discernable impact of climate change. For RCP4.5, the impact is very small and peaks around 2050 for the ensemble mean, but with a range skewed slightly towards increased emissions.

The CO_2 impact is computed as the difference between two simulations with fixed population density, the one with variable climate and CO_2 minus the one with variable climate but fixed CO_2 (Eq. 5). The resulting emissions differences (Fig. 2b) remain negative throughout the historical period until 2005 because the fixed-CO_2 simulations start out with considerably higher CO_2 levels than the variable-CO_2 ones leading to higher productivity (CO_2 fertilisation, see Hickler et al. 2008, Ahlström et al. 2012), higher fuel load and therefore higher emissions. For RCP8.5, the global CO_2 impact on emissions is about the same as the climate impact, but for RCP4.5 it is much larger. The magnitude of the CO_2 effect itself is climate dependent, which can be seen by the inter-ensemble range, which is caused solely by differences in climate. (All ensemble members use the same atmospheric CO_2 scenarios for a given RCP.) There is also a small interannual variability caused mainly by climate fluctuations, since interannual variations in atmospheric CO_2 are small until 2005 and absent from the scenarios (Meinshausen et al. 2011). As for climate, there is no discernable CO_2 impact on past emission changes.

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Finally, the demographic impact is simulated by the difference between simulations with time varying climate, CO_2 and population, and the corresponding simulations where population is fixed, but the other two vary with time (Eq. 5). As one would expect, the results for the two RCPs are indistinguishable, with a small climate-related ensemble range and a small amount of interannual variability caused by climate fluctuations (Fig. 2c). The simulated demographic impact for the central population scenario is towards declining emissions mainly driven by population growth. After 2050, the effect declines rapidly, and there is a very slight positive trend after ca. 2090 which is due to the leveling off of projected population growth (SSP2) and continuing urbanisation. As can be seen by comparing simulated emissions between the central (SSP2) and the remaining population scenarios (Fig. 1a), the demographic impact varies considerably between scenarios, with a continuing negative impact until 2100 for the scenario with high population growth with slow urbanisation (SSP3), but a positive impact of the demographic change on global emission trends from about 2040 for low population growth with fast urbanisation (SSP5).

Results for the set of sensitivity tests where the parameterisation of SIMFIRE was modified are shown in Fig. 3 for the climate, CO_2 and demographic impacts separately. Note that in this case, simulations are performed with only one ESM (MPI-ESM-LR). The climate impact on emissions is again small for RCP4.5, but discernably positive for RCP8.5 after ca. 2020. The climate impact is hardly affected by changing the SIMFIRE parameterisation. The CO_2 effect is similar to the ensemble mean (Fig. 2b), but with a marked decline after ca. 2080 for RCP8.5. In this case, SIMFIRE optimised against MCD45 burned area shows less of a positive trend after 2020 as a result of CO_2 changes than the standard formulation, and a more pronounced negative effect after 2080. Also, the simulated historical and future

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demographic impacts are slightly less for MCD45 than for the standard version. The SIMFIRE version with an initial increase in burned area with population density (Eq. 3) has only a very small impact on simulated global emissions.

The recent estimate from the GFED4.0s data set puts the average global wildfire emissions at 1.5 PgC/yr (released May 2015, 1997-2014 average of savannah, boreal and temperate forest fires combined, against 2.2 PgC/yr for all biomass burning, van der Werf et al. 2010, updated using Randerson et al. 2012 and Giglio et al. 2013), slightly higher than simulated here (Table 2). During the 20th century, global emissions decrease by around 150 TgC/yr, a little more than 10%. The main driving factor of this decrease is growing population, while climate and CO_2 changes have only a very small impact on emissions, as already discussed with Fig. 2. Further analysis of these driving factors (Fig. 4), however, reveals that this small impact is due to compensating action on either burned area (Eqs. 6 and 8) or combustible fuel load (the remainder). Globally, climate had a small positive and CO_2 a slightly smaller negative effect on emissions via burned area. At the same time, climate had a negative and CO_2 a positive impact on combustible fuel load. For the 21st century (Fig. 5), this constellation is predicted to continue, with a somewhat larger demographic impact that is negative across all ensemble members. The overall effect on emissions, however, is small and of uncertain sign (ensemble range including both positive and negative changes). This is because the climate impact and even more both CO_2 effects, acting in opposite directions, increase several fold compared to the situation during the 20th century.

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3.2 Driving factors of regional emission changes

By the beginning of the 20th century, the main wildfire emitting region is clearly Africa (Fig. 4), followed by South America, North Asia and Oceania. Emission changes towards the end of the 20th century are mainly due to changes in population density in all regions except for Europe, North America and Oceania where population growth rates are significantly lower. For Europe, climate change has led to an increase in burned area, but an about analogous decrease in fuel load, such that the overall climate effect is small and uncertain. The result for North America is similar, while there is a larger but still uncertain positive CO_2 effect on fuel load, similar to Oceania and South America. For Oceania the population effect is by far the smallest and the only one uncertain in sign (judging by the ensemble range).

The climate effect via fuel load is negative in all regions, while the climate effect via burned area is almost always positive, except for the Middle East where it is negative but with a large ensemble range spanning both positive and negative, and South Asia, where it is close to zero. We find a negative CO_2 effect via burned area in the tropics (Africa, South America), but a positive effect in the arid sub-tropics and temperate zones (Middle East, North Asia). The positive climate effect can be explained by regional changes in N_{max} (Table 3, cf. Eq. 1), which are always positive, small for changes during the 20th century, but reaching up to over 100% for Europe from the period 1971-2000 to 2071-2100 under the RCP8.5 climate change scenario. The highest increases are for the northern regions, and the smallest for regions with large deserts, like Africa and Middle East, but starting from a high base. However, climate change can also affect burned area indirectly through vegetation change by changing B or F in Eq. (1), for which a good indicator is the fraction of the total leaf area index that is attributed to grasses ("grass fraction", Table 3). This is because $a(B)$ for grassland and savannahs is about one order of magnitude larger than $a(B)$ for woody biomes (Knorr et al. 2014). There is a general increase in the fraction of woody at the expense of grass vegetation across all except the hyper-arid Middle East region. Here, the grass fraction is by far the highest and the climate too dry to support the expansion of shrubs.

For 1971-2000, simulated wildfire emissions are markedly lower than for the beginning of the 20th century for Africa, South America, South Asia and Middle East (Fig. 5). Of these regions, only Africa is predicted to continue to decline for the entire ensemble range for both RCPs. The main drivers are population growth and CO_2 impact on burned area, partly compensated by increased fuel load. For South America, South Asia and Oceania the pattern is similar, except with a much smaller demographic impact, resulting in an overall change of uncertain direction.

All northern regions (North America, Europe and North Asia) are predicted to increase emissions across the entire ensemble. All of these have a slight positive climate impact, but with large uncertainties, where climate change strongly increases burned area compensated largely by a decrease in fuel load. Since precipitation is predicted to increase in these regions (Table 1), the climate effect is mainly due to increasing temperatures and N_{max} (Tables 1, 3). For North America and North Asia there is a clear positive effect of CO_2 on fuel load which appears to be the main reason for tilting the balance towards emission increases. However, population change plays a rather small role, with a large ensemble range for Europe and North Asia making the sign of the impact uncertain given their slower population growth. For North America, the demographic impact is small, but universally slightly negative. An exception is the region Middle East, which has a large positive CO_2 effect via burned area (cf. Fig. 4).

Overall, there is a marked shift in emissions towards the extra-tropics: while for 1971-2000, the tropics have 700 TgC/yr emissions vs. 580 for the extra-tropics (ensemble mean), for 2071-2100 the split ranges between 420 tropics vs. 680 extra-tropics for RCP4.5, high population growth / slow urbanisation, and 600 tropics vs. 720 extra-tropics for RCP8.5, low population growth / fast urbanisation. As the regional analysis shows, this change is mainly the result of expanding population in Africa. However, there is also a much stronger negative climate effect on fuel load at high compared to low latitudes (Fig. 6), which to some degree slows down the shift of emissions to the north. This contrasts with a generally positive CO_2 effect across most of the globe, but with about the same magnitude for tropical and extra-tropical vegetated areas. At high latitudes, combustible fuel load is generally much higher than at low latitudes, implying that this is compensated for by a much smaller burned area, leading to overall lower emissions in this region.

3.3 Probabilistic forecast of future emission changes

For simulated emissions during the 20^{th} century, we find that a majority of ensemble members show significant increases (i.e. by more than two standard deviations) for northern boreal regions and the Tibetan plateau, and decreases for some scattered regions in Europe and China, but in general, changes are small compared to interannual variability (Fig. 7a). For the 21^{st} century, most simulations for both RCP4.5 (Fig. 7b) and RCP8.5 (Fig. 7c) predict a significant decrease in emissions in Africa, mainly north of the equator, and to a lesser degree and mostly for RCP8.5 for North Australian savannahs. The main regions for which a significant increase in fire emissions is predicted are the boreal-forest / tundra transition zones, Europe and China, and arid regions in Central Australia, southern Africa and Central Asia. For the arid regions, however, the increase is much more pronounced for RCP8.5 than for RCP4.5.

These changes in fire emissions during the 21st century relative to current variability can also be analysed by driving factor (Eqs. 4 and 5). The analysis reveals that increases in emissions in the boreal/tundra transitional zone are mostly due to climate change, except for the more continental and arid north-eastern Siberia. For the rest of the globe, the climate effect has a surprisingly small impact, being confined to narrow bands of arid regions in southern Africa, Australia and the Arabian Peninsula. Climate change also leads to a significant decrease in emissions in northern Africa and the Middle East (Fig. 8a-b, cf. Fig. 5). For RCP4.5, CO_2 has only a small positive impact on emissions, mainly for Central Asia, and a negative impact for African, South American and North Australian tropical savannahs. For RCP8.5, the CO_2 effect has a much bigger impact globally on the relative change of emissions, leading to increased emissions in large regions including Mexico, southern South America, all African, Arabian and Central Asian semi-deserts, most of the southern half of Australia, and north-eastern Siberia. The negative effect is also much more pronounced and comprises most tropical savannahs (Fig. 8c-d). This creates opposing effects for the large zone covering North Africa, Arabia and Central Asia, with climate change leading to a decrease in plant productivity and fuel load (hence lower emissions) against CO_2 change leading to CO_2 fertilisation (hence higher emissions).

For the moister and in general much more highly emitting savannahs (van der Werf et al. 2010), the dominant effect comes from CO_2 change and is negative, due to shrub encroachment. This creates an interesting situation for Australia: in the very north, higher CO_2 leads to shrub encroachment, leading to lower emissions (Fig. 7); in a central zone across the continent, climate change is the leading driver of increased

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emissions, but for most of the southern half, CO_2 change leads to enhanced water-use efficiency of the already woody vegetation (Morgan et al. 2007) causing the opposite effect compared to the north. The same pattern is repeated for southern Africa, but with a stronger positive climate effect in the central zone. The demographic effect (Fig. 8e) leads to a significant increase in wildfire emissions in Central and Eastern Europe as well as East Asia due to its projected declining population, but a decrease mainly in African savannahs but also Turkey and Afghanistan/southern Central Asia given their projected large increases in population.

4 Discussion

In this study, we find that wildfire emissions declined likely more than 10% during the course of the 20th century, in agreement with ice core measurements of the isotopic signature of carbon monoxide (Wang et al. 2010). A decline in global wildfire activity since the late 19th century was also suggested by Marlon et al. (2008) based on charcoal records, even though issues remain concerning the magnitude of the decline as and whether there have also been period of increasing emissions (van der Werf et al., 2013). In the present simulations, the decline is caused overwhelmingly by increasing population density, in agreement with the results of Knorr et al. (2014) who used SIMFIRE alone to simulate burned area, without coupling to LPJ-GUESS, driven by the same historical population data. According to the present study, population effects dominated because a positive effect of climate change on burned area was compensated by a negative effect on fuel load, and a negative effect of CO_2 increase on burned area was compensated a positive effect on fuel load. This broad general pattern, found for the main active wildfire regions, is predicted to continue throughout the 21st century, albeit with much stronger climate

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and CO_2 effects, while the negative population effect on emissions continues to have about the same magnitude.

This dominant pattern of opposing climate and CO_2 effects, and opposing effects via burned area and fuel load, calls for a mechanistic explanation. A positive impact of climate change on burned area or numbers of fires is what is commonly expected (Krawchuck et al. 2009, Pechony and Shindell 2010) and it was found for all regions in agreement with simulated changes in fire risk (N_{max} in Eq. 1). The exception is the Middle East region during the 20th century, with a negative climate impact on burned area, which is likely caused by a decline in fuel continuity which suppresses the spread of fires (reduced F in Eq. 1). A negative climate impact on fuel load is consistent with the widely expected positive climate-carbon cycle feedback (Friedlingstein et al. 2006), whereby rising temperatures increase soil and litter respiration rates, releasing CO_2 from the terrestrial biosphere. The faster decomposition of litter under warmer conditions, incorporated into LPJ-GUESS (Smith et al. 2001), leads to a reduction in fuel available for combustion (Knorr et al. 2012). Since combustion by fire is nothing more than a shortcut for litter decomposition, higher temperatures simply shift the balance between the two processes towards microbial decomposition. However, the opposite climate effect could also be expected, where warming leads to increased productivity in boreal, temperature-limited ecosystems, leading to increased fuel production (Pausas and Ribeiro 2013). For the present study, at least, this situation does not play a global role and is only found for scattered regions of north-eastern Canada and northern Russia (Fig. 6b).

A positive effect of CO_2 on fuel load, which is found to be active almost everywhere across the globe, is fully consistent with the notion of CO_2 fertilisation of the terrestrial biosphere (Long et al. 1996, Körner 2000), whereby higher atmospheric CO_2 concentrations increase the rate of carboxylation, increasing net primary production and thus fuel load (Hickler et al. 2008). However, we also find a negative impact of rising CO_2 on wildfire emissions for all tropical savannah ecosystems, which outweighs the positive impact through increasing fuel load and is caused by an increase in the dominance of woody at the expense of grass vegetation. This phenomenon of shrub encroachment, or woody thickening, in tropical savannahs has been repeatedly observed in field studies (Wigley et al. 2010; Bond and Midgley 2012) and frequently attributed to CO_2 enrichment of the atmosphere (Morgan et al. 2007; Buitenwerf et al. 2012). This link is less observed for arid savannahs (Bond and Midgley 2012), consistent with the finding here that in the most arid regions, no decrease in the grass fraction is predicted. This result differs partly from that by Lasslop and Kloster (2015), who also found emissions per area burned during the 20th century, but a 40\% overall increase in emissions with approximately half of the increase due to increasing burned area.

On a global scale, according to the present simulations, the level of future wildfire emissions is highly uncertain for a scenario of moderate greenhouse gas increases (RCP4.5), with the ensemble mean showing slightly lower emissions towards the end of the 21^{st} as opposed to the end of the 20^{th} century. For a high, business-as-usual scenario of greenhouse gas forcing (RCP8.5), the ensemble mean points towards an increase across the same time span, but with a range including both positive and negative changes. There is also a general trend towards increases during the second half of this century. The slight bias towards increased emissions is the result of a combination of increased fire risk due to warming, and increased fuel load due to CO_2 fertilisation, but with population growth, woody thickening and faster litter decomposition all counteracting. We therefore find that climatic impacts on fire risk are only one of many, often opposing factors that might lead to increased wildfire emissions in the future.

The future demographic dynamics can lead to a wide range of future wildfire emissions. In addition to its indirect impact on wildfire emissions through interactions with economic and technological changes contributing to GHGs emissions and climate change, changes in population size and spatial distribution play a direct and important role for fire prevalence, as an ignition source but predominantly as fire suppressors. While fertility decline is occurring in almost all global regions, the population momentum will continue to drive global population size upward for at least some years and likely contribute to continuously declining wildfire frequencies. The uncertainty of future population dynamics, however, leads to a wide range of population trends and causes large variations in simulated wildfire emissions. Moreover, the same changes in population sizes can result in rather different emissions due to variations in spatial population distribution, particularly through different urbanisation patterns. While the whole world is expected to be further urbanised, variations in speed and patterns of urbanisation across regions and over time can lead to significantly different wildfire patterns.

Simulated emissions presented here generally agree with similar results with a coupled fire-vegetation-biogeochemical model by Kloster et al. (2012), insofar as climate only starts to impact on fire during the course of the 21st century, but not before, and that changes in population density generally lead to lower emissions. The difference is that in the present study, climate has a much smaller impact on emissions, ranging between 0 and +20% for RCP8.5 and few percent at most for RCP4.5. A similar study reporting simulations of increasing fire emissions for Europe

(Migliavacca et al. 2013a) reports an increase for Europe of about 15 TgC yr^{-1} until the late 21st century, when measured for the same reference period as here, which is within the ensemble range found in this study. Even though they used the same Community Land Model, their fire parameterisation (Migliavacca et al. 2013b) differed from the one used by Kloster et al. (2012).

The difference between the present study and the one by Kloster and co-workers might be due to the pronounced negative effect of temperature change on fuel load, and of CO_2 on burned area, found here. Another important difference is their study included deforestation fires, and employed the more common approach of representing the impact of population density by a combination of number of ignitions times an explicit function of fire suppression, the combination of which leads to a small decrease in emissions during the 21st century. This approach, based on Venevsky et al. (2002), always leads to an increase in burned are if ignitions increase, all else being equal. No decline is simulated during the 20th century, neither due to changing population density, nor land use. This study, by contrast, uses a semi-empirical approach with a functional form of the relationship between burned area and population density derived by optimisation against observed burned area and simulates the historical decline that is suggested on the basis of ice core and charcoal records. The implicit assumption here is that that for most of the world, except for areas where population density is very low, the fire regime is ignition saturated (Guyette et al. 2002), in contradiction to the approach by Venevsky et al.~(2002). This means that above a threshold of typically 0.1 inhabitants per km^2, burned area becomes independent of human population density (cf. Knorr et al. 2014). However, if we assume some increase in burned area with population density below the threshold, the results change only little (Fig. 3). Therefore we argue for universal ignition saturation as a reasonable approximation at the scales considered in the present study. We also expect possible future increases in lightning activity (Romps et al. 2014) to have only a marginal effect on burned area and thus emissions.

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An important outcome of this study is that it predicts are large shift in fire emissions from the tropics towards the extra-tropics, driven by two coinciding effects causing a secular decline in emissions in African savannahs and grasslands: CO_2 increases driving woody thickening, in turn making the vegetation less flammable (Bond and Midgley 2012), and population growth leading to decreased burned area (Archibald et al. 2008). The impact of this shift on the global budget of carbon emissions from wildfires is so large because these regions currently have by far the largest emissions worldwide (van der Werf et al. 2010). In agreement with observed evidence (Bond and Midgley 2012), the negative CO_2 effect on emissions via burned area is limited to the semi-humid tropics and does not play a role either in the most arid regions, nor at higher latitudes. It is also not simulated for South Asia, where most of the potential semi-humid grasslands and savannahs have long been converted to agriculture. For the mostly arid region Middle East, we find that a strong positive CO_2 effect via burned area is the larger contributor to emission change during the 20th century, and the biggest during the 21st. This leads to a marked increase in emissions for RCP8.5, outcompeting negative impacts of growing population and climate change on fuel load and driven by a marked decline in precipitation (Table 1), while during the 20th century, there is a marked negative impact of climate change on burned area. Here, CO_2 fertilisation leads to denser vegetation, increasing fuel continuity (higher F in Eq. 1), thus leading to higher burned area, while decreasing precipitation results in a lower F. To a lesser extent this is simulated for North Asia, which also contains large, highly arid regions, but with a positive ensemble-mean climate effect on burned area.

For both regions, however, the ensemble spread is very large making the projections highly uncertain.

For Australia, we find an interesting zonal pattern of changing effects from the northern savannahs to the arid southern coast. In the very north, woody thickening due to higher CO_2 leads to decreased emissions through decreased burned area, with negligible climate effects. This is followed by a central zone where both climate and CO_2 change lead to increased emissions, and a third zone comprising the southern half of the Australian interior where CO_2 fertilisation leads to increased emissions via higher productivity. Population change plays almost no role for changing emissions in this region. As a result, the north is predicted to decrease significantly in emissions, while for the central zone where climate and CO_2 effects overlap, and for the south there is no clear signal in the prediction. A similar tri-zonal pattern is also predicted for southern Africa stretching from the Miombo woodlands across the Kalahari to the Cape region. This zonal differentiation resembles the results by Kelley and Harrison (2014), who simulated a reduction in burned area in North Australia due to CO_2 driven woody thickening, but an increase in burned area in the Australian interior due to enhanced fuel continuity with denser vegetation caused by CO_2 fertilisation.

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5 Conclusions

We find that since the early 20th century, wildfire emissions have been steadily declining due to expanding human population, but that this decline will only continue if climate change and atmospheric CO_2 rise is limited to low or low/moderate levels, population continues to grow and urbanisation follows a slow pathway in the next decades. Otherwise, it is likely that the world is currently in a historic minimum regarding wildfire emissions, and the current declining emission trend will reverse in the future at higher latitudes, departing from the current domination of African savannahs. Emissions, however, are unlikely until 2100 to again reach early 20th century levels. The predictions are based on an ensemble of climate and population/urbanisation projections, but a single fire model albeit tested for the impact of different parameterisations. The results generally show a large ensemble spread, and also reveal widely opposing factors influencing future emissions, complicating the task of predicting future wildfire emissions. We find that apart from climate leading to higher fire risk, equally important factors on a global scale are demographic change, woody thickening in savannahs with higher CO_2 levels, and faster woody or grass litter turnover in a warmer climate, both leading to declining emission, as well as CO_2 fertilisation generally leading to higher fuel loads or fuel continuity and thus increased emissions. Therefore, the common view of climate warming as the dominant driver of higher future wildfire emissions cannot be supported.

This work is assumes that fire management for a given fire and vegetation regime will remain unchanged. New fire policies that go beyond simple fire suppression and thus avoid large-scale fuel build-up and ultimately increased risks of large fires could very well counteract the effects of climate change and thus lead to a better co-existence between humans, natural ecosystems and wildfires.

Author contribution

W. K. conceived the study, carried out model runs, performed the analysis and wrote the first full draft of the manuscript, L. J. provided the population scenarios, all authors contributed to discussions of results and writing.

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