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Impact of fuel variability on wildfire emission estimates

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HIGHLIGHTS

- We assess the potential error in fire emission inventories due to constant fuel load.
- Seasonal variations in fuel do only have minor impacts on emissions.
- CO_2 increase since 1850 leads to an increase in fire emissions of almost 40%.

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ABSTRACT

Atmospheric composition is strongly influenced by wildfire emissions, which have a strong variability over time and space. Estimates of fire emissions on large scale are based on a combination of burned area, combustion completeness, and fuel load. Approaches differ in the derivation of this information, which involves models and observations to different degrees. Due to the lack of highly spatially and temporally resolved observations the variability of fuel load is often not fully taken into account.

The fuel load can differ between seasons due to variations in the vegetation productivity, decomposition rates and fire occurrence. On the longer time scale the effect of CO_2 fertilization is expected to influence the vegetation productivity and therefore overall fuel load abundance. All these processes are accounted for in land carbon cycle models. We use the land surface and vegetation model JSBACH as a tool to understand the influence of fuel load seasonality, fuel load variability within land cover types and CO_2 fertilization on fire occurrence and wildfire emissions.

We find that using the mean fuel load over time for each grid cell instead of seasonally varying fuels leads to comparable burned area and emissions (only 3% deviations from the reference). Using minimum or maximum values, however, leads to strong under (0.54 times the reference) and overestimation (1.85 times the reference) of the emissions. When using constant fuel load for each vegetation type strong regionally varying, over and underestimations of emissions are found. Over the 20th century CO_2 fertilization strongly impacts fuel availability. As a consequence, burned area and carbon emissions are almost 20 and 40% higher at present day.

In general, our results confirm the applicability of time constant fuel loads in emission estimation methods for present day, as the seasonality is of minor importance. However, we suggest that considering the variability of fuel driven by climate variability in space can improve the estimates. This result is in line with a number of studies highlighting the importance of fuel limitation for the occurrence of fire. On the longer time scale the influence of CO_2 fertilization is not negligible according to our results, but high uncertainties in the understanding of the process increases the difficulty to account for it in fire carbon emission approaches. This assessment of potential errors in fire emission datasets should help to further improve approaches to estimate fire emissions and to interpret available datasets and differences between them.

1. Introduction

Wildfire emissions can have strong impacts on the atmospheric composition depending on the amount, the location and the prevalent meteorological conditions (Langmann et al., 2009). For some atmospheric pollutants biomass burning is an equally important source as the burning of fossil fuel (Bowman et al., 2009;

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Crutzen and Andreae, 1990). The composition of the atmosphere is important for air quality and climate (Keywood et al., 2013). Global gridded trace gas and aerosol emissions are a valuable dataset for a number of applications in these fields (Lamarque et al., 2010; Marlier et al., 2014).

Wildfire emissions are estimated by combining an estimate for the area burnt with an estimate of the fuel load and information on the combustion completeness (Seiler and Crutzen, 1980). One exception is the estimation of emissions based on the fire radiative power (Kaiser et al., 2012). The approaches starting from the burned area are often based on constant or region specific biomass densities of vegetation types (Hoelzemann et al., 2004; Mieville et al., 2010; Reid et al., 2009; Wiedinmyer et al., 2011). The biomass densities are usually based on vegetation models. More recently carbon cycle models are used interactively to estimate the amount of available fuel, spatially and temporally resolved, on the model grid resolution and prescribing burned area as a boundary condition in the model. This approach does take into account the impact of fire on the fuel load, i.e. after a fire the fuel load will be reduced (Turquety et al., 2014; van der Werf et al., 2010). Land carbon cycle models including a fire model allow a consistent computation of fuel load, burned area and fire emissions for present day (Arora and Boer, 2005; Kloster et al., 2010; Lasslop et al., 2014; Prentice et al., 2011; Thonicke et al., 2010; Yue et al., 2014) or the past (Brücher et al., 2014; Martin Calvo et al., 2014; Pfeiffer et al., 2013). Although large improvements in fire models have been achieved (Kelley et al., 2013), the uncertainty in modelled burned area is high. Therefore the constraint by observations on burned area is usually the preferred input for estimates on fire emissions.

Retrievals of burned area are a rather recent product of the remote sensing community. Active fire counts cover a longer time period and are used in a number of studies instead of burned area (Mieville et al., 2010; Reid et al., 2009; Wiedinmyer et al., 2011). Approaches using active fire counts need an additional assumption on the fire size, this is assumed constant, for instance in Wiedinmyer et al. (2011) 0.75 km^2 for grasslands and savannas and 1 km^2 otherwise, or based on a vegetation type specific relationship between fire count and burned area data (Mieville et al., 2010). However, the relationship between fire count and burned area is itself a function of fuel load as higher fuel loads can cause a higher rate of spread.

Using constant fuel loads over time may influence certain characteristics of the emission estimate, it may change the total amount of emissions, the spatial distribution or the magnitude of the seasonal emission peak. Using constant fuel loads per vegetation type may change the relation between emissions and climatic drivers, as the influence of climate on fuel load within a vegetation type is neglected. In addition, the emissions of different trace gases and aerosols may respond differently as the emission coefficients which express the ratio of emitted species to emitted carbon, vary between vegetation types. Changes in seasonality may be important for the short term impacts of wildfires such as atmospheric chemistry and air quality. On the decadal to centennial time scale (especially for the last century and coming decades) CO_2 fertilization may be a process that can strongly influence the fuel availability, especially in dry lands where fire activity is high.

Here, we use a modelling approach to assess the uncertainty in fire emissions due to the variability in fuel load caused by the seasonality, variations within vegetation types and CO_2 fertilization over the 20th century. We quantify the impact of the fuel variability by comparing the wildfire emissions of a reference simulation to a number of sensitivity simulations. The reference simulation uses the historical CO_2 increase, fuel loads and fire emissions are simulated interactively in a global vegetation model. In the sensitivity simulations fuel loads, burned area or CO_2 fertilization are subsequently altered.

2. Methods

2.1. Model

This study applies the global vegetation model JSBACH (Brovkin et al., 2013; Raddatz et al., 2007; Reick et al., 2013; Schneck et al., 2013), which is the land surface component of the MPI Earth system model (Giorgetta et al., 2013). The JSBACH model includes a processed-based representation of the global carbon and hydrological cycle. This model was recently extended by including the process based fire model SPITFIRE (Lasslop et al., 2014; Thonicke et al., 2010). The carbon cycle of the JSBACH model includes pools for different components of living and dead biomass above and below ground. These pools are used as input to the fire module and represent the fuel load. The fuel load is further separated into different size classes that are commonly used in fire modelling. The relative contributions of size classes determine how fast the available fuel dries out. Fine fuels dry faster, than coarse fuels. The fine fuels allow the fire to spread faster and they burn more complete compared to larger-sized fuels. A full model description and evaluation of the fire model can be found in (Lasslop et al., 2014). The fire model does not include burning of crops, peatlands or deforestation fires. Peatlands are not limited in fuel load and seasonality is of minor importance. Croplands are strongly managed and burning takes place during certain times of the year. The full seasonality is also here of minor importance, as croplands will not be burned just before harvest where the amount of biomass would be highest, but rather outside the growing season.

The emissions of selected trace gases and aerosols were derived as the product of burned area (BA), fuel load (FL), combustion completeness (CC) and emission factor (EF) of the specific trace gas or aerosol.

$$emission = BA \cdot FL \cdot CC \cdot EF \qquad (1)$$

We used the emission factors provided by Akagi et al. (2011). The emission factors for the land cover types used here are given in Table 1. The emission factors are assigned to the modelled carbon emissions based on the dominant fire type map used in the GFAS dataset (Kaiser et al., 2012).

2.2. Model simulations

Fuel load does impact wildfire emissions through two factors. First, the amount of fuel load available for burning controls directly the fuel consumption and the resulting wildfire emissions. Second, the fuel load controls the fire spread rate. With more available fuel the spread rate is typically higher, which leads to a higher burned

Table 1
Emission factors from Akagi et al. (2011). We used the values for pasture maintenance for the grass regions, as large areas of the grass covered land surface are used as pasture. For the emission factor of organic carbon no values for boreal and temperate forest where given and we used the value for the extra-tropical forest for both land cover types. For black carbon we used the mean value of the range given.

Emission factor [g kg^{-1}]	CO_2	CO	CH4	NOx	PM2.5	OC	BC
Grass	1548	135	8.71	0.75	14.8	9.64	0.91
Savanna	1686	63	1.94	3.9	7.17	2.62	0.37
Shrub	1710	67	2.51	3.26	11.9	3.7	0.2
Boreal forest	1489	127	5.96	0.9	15.3	9.15	0.56
Temperate forest	1637	89	3.92	2.51	12.7	9.15	0.56
Tropical forest	1643	93	5.07	2.55	9.1	4.17	0.52

area. Emission inventories that are based on observed burned area data do implicitly take into account the second factor. Emission inventories, however, that are based on fire count data, do apply a constant relationship between burned area and fire counts and thus ignore the impact of fuel load on the burned area itself (Reid et al., 2009; Wiedinmyer et al., 2011).

We performed simulations that reflect these two types of emission inventories (see Table 2):

1. Burned area is a function of the available fuel: Compared to the reference simulation the model simulation MEAN, MIN, MAX and PI_CO2 differ with respect to the burned area as well as fuel consumption (fire emissions per burned area). The differences of these simulations to the reference serve as a measure of potential errors in approaches based on fire count data, that do not account for the effect of fuel load on burned area extent, but rather prescribe a constant burned area per fire count.
2. Burned area of the reference simulation is combined with the fuel consumption (C emissions per burned area) of the simulation with prescribed fuel load: Compared to the REF simulation the simulations MEAN_BFref, MIN_BFref, MAX_BFref, AVG_PFT_BFref and PICO2_BFref use the same burned area but differ in the fuel consumption. The fuel consumption is derived from the MEAN, MIN, MAX and PI_CO2 simulation. The difference of these emission estimates to the reference simulation illustrates the potential error for approaches using burned area as input.

The reference simulations interactively simulated the fuel load. For the reference simulation the model was spun up to achieve equilibrium of the carbon pools under preindustrial conditions (year 1850) followed by a historical transient simulation until 2005. We used the CRUNCEP meteorological forcing dataset and atmospheric CO_2 concentrations (Sitch et al., 2013) as input to our land surface model JSBACH. Land use and land use change were prescribed according to the protocol described in Hurtt et al. (2011). The simulations were performed on a spatial resolution of T63, which equals $1.875° \times 1.875°$. For our simulations with prescribed fuel loads we use a sub part of the model (CBALONE) that performs computations of the carbon allocation, respiration, land use and land use change, and disturbances by using input from a simulation with the full land surface model (net primary production, leaf area index, atmospheric and soil parameters) (Schneck et al., 2013). This model setup is capable of reproducing exactly the results of the full JSBACH model with respect to the land carbon cycle, with low computational costs. In simulations with prescribed fuel loads, the fuel loads are derived from the reference simulation over the years 1997–2005. Then the model is applied over the same years (1997–2005) using the prescribed fuel load. The meteorological and hydrological parameters are the same in simulations using prescribed fuel load as in the reference simulation. The fuel loads for the simulations with prescribed fuel loads apply mean, maximum and minimum values of the monthly model output of the reference simulation over the years 1997–2005 for each grid cell. Another simulation applies average fuel loads for each plant functional type (PFT) considered in the model, again based on the period 1997–2005. The average fuel load for each PFT was derived by averaging over all grid cells with a cover fraction of the specific PFT higher than 0.3. JSBACH thereby distinguishes between 11 PFTs, 2 tropical and 2 extra-tropical tree types, two shrub types, C3 and C4 natural grass, C3 and C4 pasture, and crops. The differentiation between 11 PFTs is comparable to other studies. Hoelzemann et al. (2004) and the FINN emission inventory (Wiedinmyer et al., 2011) for example distinguish between 5 vegetation types and 10 regions. Mieville et al. (2010) use 14 land cover types and Reid et al. (2009) use ten categories to map PM2.5 emissions to each active fire hotspot.

The reference simulation is repeated with fixed pre-industrial atmospheric CO_2 concentrations to isolate the impact of CO_2 fertilization on wildfire emissions.

In all cases the comparison between simulations is based on grid cells where fire occurs in the reference simulation. This ensures consistency with the emission datasets which are all based on indicators of fire occurrence and therefore emissions in regions that are never influenced by fires cannot occur.

Table 2
List of experiments with name, the period of simulation and a description of fuel load, burned area CO_2 concentration used in the simulation. Burned area and fuel load are used either prescribed or computed interactively. Prescribing fuel loads in the model is done by prescribing vegetation and litter carbon pools. The mean, min and max values used as prescribed fuels are based on the monthly output of each grid cell over the years 1997–2005 of the REF simulation. For the AVG_PFT simulation the fuel load is averaged using the same data but applying the average per plant functional type (PFT) not per grid cell.

Experiment	Time	Fuel load	Burned area	CO_2
REF	1850–2005	Interactive	Interactive	Transient
PICO2	1850–2005	Interactive	Interactive	Preindustrial
PICO2_BFref	1850–2005	Interactive	Ref	Preindustrial
MEAN	1997–2005	Mean (REF)	Interactive	REF
MEAN_BFref	1997–2005	Mean (REF)	REF	REF
MIN	1997–2005	Min (REF)	interactive	REF
MIN_BFref	1997–2005	Min (REF)	REF	REF
MAX	1997–2005	Max (REF)	interactive	REF
MAX_BFref	1997–2005	Max (REF)	REF	REF
AVG_PFT	1997–2005	Mean (REF,PFT)	interactive	REF
AVG_PFT_BFref	1997–2005	Mean (REF,PFT)	REF	REF

2.3. Data

We evaluate the applicability of the vegetation model for the assessment of the importance of the variability of fuel on the fire carbon emissions by comparing the model output to two observational datasets. For the seasonality we use a satellite product for the fraction of absorbed photosynthetically active radiation (FAPAR) based on the SEAWIFS sensor (Gobron et al., 2006). To evaluate the modelled amount of biomass we use a product for the forest biomass which is available for the tropics (Saatchi et al., 2011). The dataset by Saatchi et al. (2011) provides estimates for above, below and total living tropical forest biomass, which we compare to the total modelled carbon stored in woody vegetation, above and below ground.

In addition, we compare the global mean emission estimates to the emissions of the GFED version 3 database (van der Werf et al., 2010). These estimates are derived by prescribing burned area derived from the MODIS sensor (Giglio et al., 2010) in a carbon cycle model (CASA) which is mainly driven by a satellite based FAPAR dataset (van der Werf et al., 2010). It therefore includes more observational information than the model used in the present study, in which FAPAR and burned area is modelled.

We applied the R software package for data analysis and graphics (Core Team, 2014).

3. Results and discussion

3.1. Biomass and seasonality of the vegetation activity

The JSBACH model including SPITFIRE has been evaluated with respect to burned area and carbon emissions (Lasslop et al., 2014). As for this study the seasonality of fuel and the stored biomass is of major importance we evaluate here the land carbon cycle more in detail. Globally there is no data product available for the evaluation of the variability or amount of available fuel. The variability of available fuel is related to the productivity of vegetation, which is captured well by the fraction of absorbed photosynthetic radiation (FAPAR), while the amount of new fuel is related to the amount of biomass. We therefore compare the amount of modelled tropical tree biomass and the seasonality of FAPAR to satellite data based datasets. While the two variables do not directly correspond to the fuel load, they represent the most important input for the computation of the available fuel. We compare observed and modelled FAPAR on a regional basis to evaluate the performance of the seasonal variability in the carbon cycle model used in this study. We show both, the absolute values and the values normalized between zero and one (Fig. 1). The modelled seasonality of FAPAR generally agrees well with the data although a shift of one or two months is present in some regions, where in most cases the model being slightly behind the observations. Most regions show a good agreement with respect to the absolute values of FAPAR, but there is a clear tendency of the modelled values to be higher than the observed. However, FAPAR products are themselves still uncertain. For instance the CYCLOPES and MODIS products have consistently higher values than the product of the JRC (SEAWIFS) which we applied in our analysis (McCallum et al., 2010). Therefore, we do not see the slight overestimation when compared to the SWEAWIFS product as critical.

In general the modelled estimates of tropical forest biomass carbon agree reasonably well with the satellite based observational dataset. We find that the model overestimates tropical biomass in the inner tropics and underestimates the forest biomass in the dry regions (Fig. 2). Overall we consider our model a valid tool to investigate the influence of fuel variability on wildfire emissions.

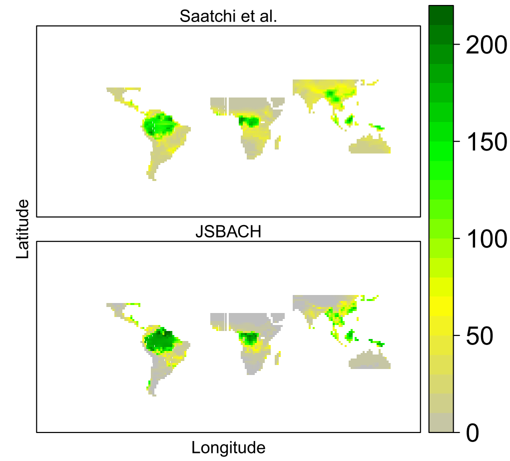

Fig. 2. Modelled and observation based tropical forest biomass carbon [Mg ha^{-1}].

3.2. *Influence of fuel load seasonality and variations within plant functional types*

Here, the influence of the seasonal dynamics in fuel loads is investigated by comparing a reference simulation with interactively computed fuels (simulation REF) to simulations where the available fuels were fixed to its mean (MEAN), minimum (MIN) and maximum (MAX) values for each grid cell. The importance of within PFT variations is further assessed by prescribing the average value for each PFT (AVG_PFT). In addition we separate the influence of fuel on both burned area and carbon emissions together from the

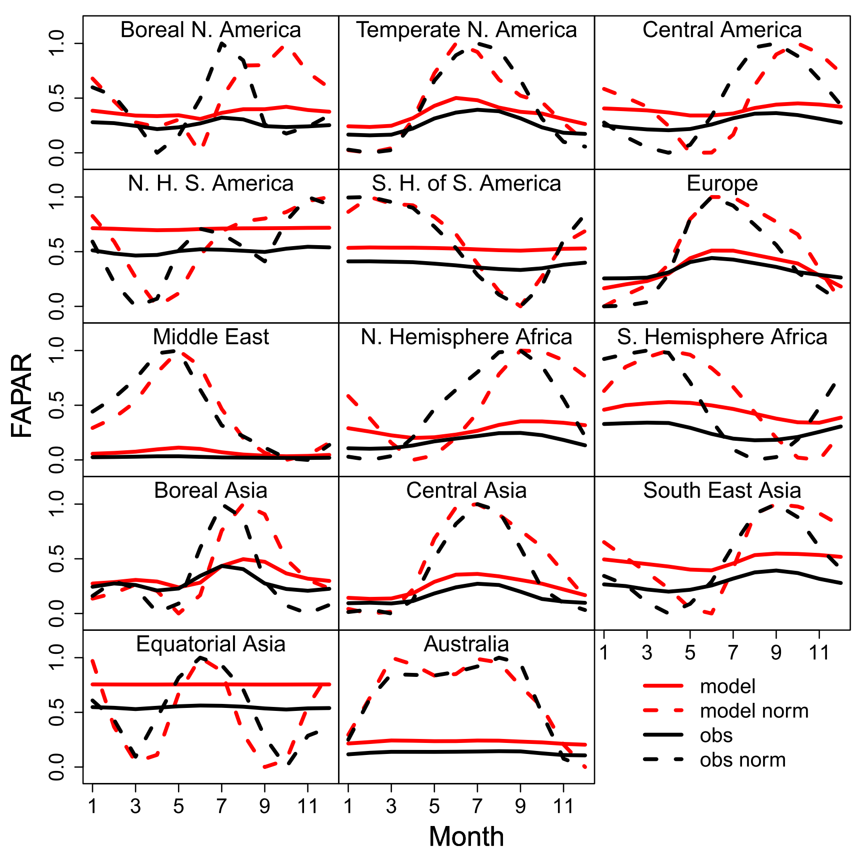

Fig. 1. Modelled and satellite (SeaWiFS) FAPAR (solid lines) and normalized modelled and satellite FAPAR (dashed lines) for different regions.

influence of fuel on the carbon emissions excluding the effect on burned area to mimic the potential error of different approaches for the estimation of biomass burning emissions. We first show the changes in the annual mean values followed by the influences on the seasonality of carbon emissions.

3.2.1. Annual mean fire emissions

The annual mean emissions of the REF simulation and the MEAN simulation lead to very similar results. Only small differences occur for the global value (Table 3). For the different trace gases and aerosols the global differences in emissions are between 0.5 and 3% (Table 3), with the MEAN simulation always being lower. Prescribing the burned area from the REF simulation (MEAN_BFref) the differences are with 1.2–2.2% very similar. The MIN and MAX simulation show stronger deviations from the REF simulation, and the over and underestimations are similar for all selected trace gases and aerosols (43–48% lower for the MIN simulation and 84–89% higher for the MAX simulation). Removing the influence of changes in burned area strongly reduces the differences (21–22% lower for the MIN_BFref simulation and 20.6–21.5% for the MAX_BFref simulation). From this we conclude that the applied model is sensitive to the seasonal variability of fuel as it shows strong differences using the minimum and maximum fuel loads. The mean fuel load, however, is a reasonable simplification to gain reliable emission estimates.

The AVG_PFT simulation shows stronger differences to the REF simulation, for example 22% lower emissions for PM2.5 and 39% lower emissions for NOx. Here, using the burned area of the reference simulation strongly reduces the deviations of the emissions to in between 3% overestimation and 6% underestimation, i.e. a large part of the differences are caused by the impact of the fuel load on the burned area. The strong influence of fuel on fire occurrence is in agreement with various previous studies (Archibald et al., 2009; Bradstock, 2010; Krawchuk and Moritz, 2011; Staver et al., 2011; Van Der Werf et al., 2008).

Due to the short lifetime of aerosols and many trace gases, not only the global value of emissions matters but also the spatial distribution is important for many applications. The spatial patterns for the model simulations REF and MEAN are similar (Figs. 3 and 4). Regionally, differences can be positive or negative depending on the seasonality of fuel load and fire season. If the seasonality of fuels and fire is in phase (correlated), constant fuels will lead to a reduction of emissions. In regions with anticorrelated mean fuel load and fire season, constant mean fuels will enhance the carbon emissions. The MIN and MAX simulations show globally lower (46%) and higher (85%) total carbon emissions, respectively with a similar spatial distribution as the REF simulation (Figs. 3c,d,4b,c). The AVG_PFT simulation shifts carbon emissions into regions that were previously fuel limited (e.g. South Africa, western part of South America) (Fig. 4d). This fuel limitation is caused by climate drivers, such as precipitation, and their influence on vegetation productivity. When applying an average fuel load for each PFT, the model simulates fire emissions in regions where the fuel load is in reality too low to support a fire. This means that the distribution of emissions along a precipitaion gradient is shifted (Fig. 5). This shift in carbon emissions with respect to precipitation only occurs for the AVG_PFT simulation, the other simulations agree in a peak at 1000 mm annual precipitation (Fig. 5). The AVG_PFT_BFref simulation, in which the burned area of the REF simulation is prescribed, shows a strong reduction of this deviation, but the shift of carbon emissions to dryer regions is still present through an overestimation in regions with precipitation below 700 mm and underestimation for higher precipitation compared to the REF simulation (Fig. 5).

The differences in terms of annual global emissions and spatial distribution to the reference simulation are stronger in the

Table 3
Emissions given in Tg year^{-1} and relative to the REF simulation. The first column is the emission values of the GFED version 3 database (available on globalfiredata.org) (van der Werf et al., 2010). The fuel load is given as a mean value per vegetated area (excluding croplands as they are excluded in the fire algorithm).

[Tg year^{-1}]	GFED v3	REF	MEAN	MIN	MAX	AVG_PFT	PI_CO2
CO_2	7069	6986	6869	3761	12,938	4826	5210
CO_2 rel	–	–	0.983	0.538	1.852	0.691	0.746
CO	372.0	399.7	390.0	220.1	743.0	292.4	295.5
CO rel	–	–	0.976	0.551	1.859	0.732	0.739
CH4	20.66	19.69	19.08	10.84	37.19	15.38	14.49
CH4 rel	–	–	0.969	0.550	1.889	0.781	0.736
BC	2.201	2.356	2.293	1.276	4.439	1.692	1.748
BC rel	–	–	0.973	0.541	1.884	0.718	0.742
OC	19.25	24.84	24.14	13.95	45.98	18.94	18.23
OC rel	–	–	0.972	0.562	1.851	0.763	0.734
PM2.5	32.08	46.66	45.53	25.78	86.57	35.67	34.42
PM2.5 rel	–	–	0.976	0.552	1.855	0.764	0.738
NOx	10.25	10.84	10.77	5.65	19.95	6.64	8.19
NOx rel	–	–	0.994	0.522	1.841	0.613	0.76
Fuel load [kg m^{-2}]	–	3.8	3.8	3.5	4.0	3.8	3.4
			MEAN _BFref	MIN _BFref	MAX _BFref	AVG_PFT _BFref	PI_CO2 _BFref
CO_2			6871	5478	8441	6847	6155
CO_2 rel			0.984	0.784	1.208	0.98	0.881
CO			391.9	316.0	483.1	404.1	353.4
CO rel			0.981	0.791	1.209	1.011	0.884
CH4			19.25	15.55	23.93	20.31	17.45
CH4 rel			0.978	0.790	1.215	1.032	0.886
BC			2.308	1.850	2.863	2.379	2.085
BC rel			0.980	0.785	1.215	1.010	0.885
OC			24.33	19.81	29.96	25.69	21.99
OC rel			0.979	0.797	1.206	1.034	0.885
PM2.5			45.76	36.94	56.36	47.42	41.24
PM2.5 rel			0.981	0.792	1.208	1.016	0.884
NOx			10.70	8.40	13.08	10.13	9.51
NOx rel			0.988	0.775	1.207	0.935	0.877

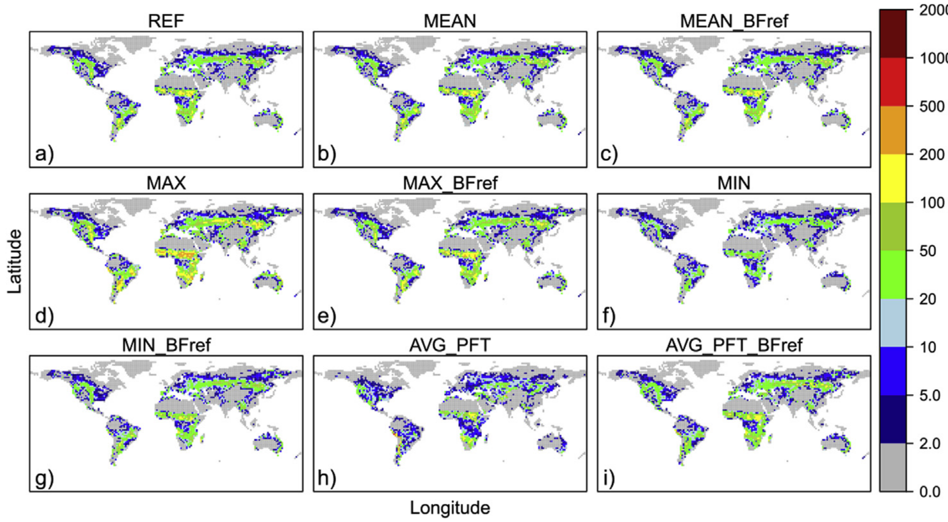

Fig. 3. Annual mean carbon emissions in g C m^{-2} year^{-1} for the REF, MEAN, MIN, MAX and AVG_PFT simulation.

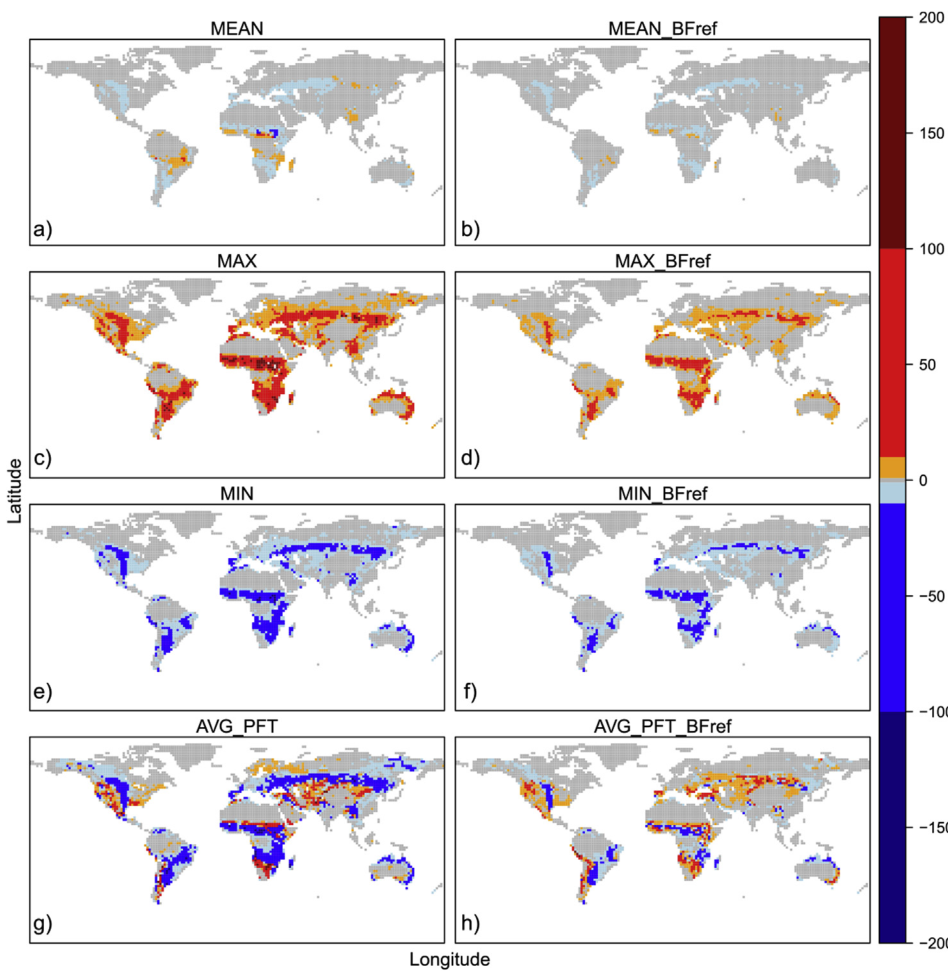

Fig. 4. Difference in annual mean carbon emissions to the REF simulation in g C m^{-2} year^{-1}, for the MEAN, MIN, MAX, AVG_PFT simulation. Positive values denote lower values and negative values indicate higher values in the REF simulation.

simulation with fuel loads constant per PFT (AVG_PFT, avg_PFT_B-Fref) compared to the simulations with fuel loads averaged per grid cell (MEAN, MEAN_BFref). We conclude from this that the fuel variability within PFT is more important to be considered than the seasonal fuel variability. The separation into vegetation types differs between models and between data based approaches, a more detailed differentiation might already help to capture more of the spatial variability. Empirical relations between fuel load and

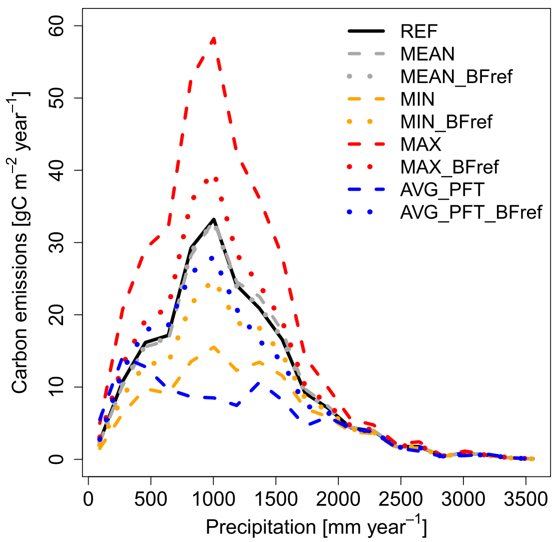

Fig. 5. Mean annual carbon emissions g C m^{-2} year^{-1}, for regions with the same mean annual precipitation.

climatic variables, such as precipitation, could be a way to improve the spatial variation of fuel load estimates based on PFTs, without applying complex process-based vegetation models. In model based approaches the bias may analogously increase with coarser resolutions due to the same effect of averaging in space.

3.2.2. Temporal variability

The temporal variability of emissions has strong influences on air quality. Emissions emitted within a short time affect the air quality more than the same amount of emissions spread over a longer time period (Marlier et al., 2014). Maximum concentrations in the air will be lower in the latter case. The MEAN simulation shows almost identical seasonal variations compared to REF (Fig. 6). The seasonality of fuels therefore does not influence the seasonality on regional scale. The MIN and MAX simulations show lower and higher peak values, respectively. The AVG_PFT shows a different seasonality in some regions. In contrast to having prescribed fuel loads per grid cell, prescribed fuel loads per PFT can change the spatial distribution of available fuels. The difference in timing of the fire season over space, can lead to a different seasonality of emissions when averaging over the regions. For all simulations the difference to the reference simulation is strongly reduced when the same reference burned area is used.

3.3. Influence of carbon dioxide increase since the year 1850

In the model the atmospheric CO_2 concentration affects the vegetation by increasing the photosynthetic uptake and decreasing the transpiration due to more closed stomates.

Here, we compare the reference simulation (REF) with the simulations PI_CO2, where the burned area responds to changes in fuel load, and PI_CO2_BFref, in which the burned area of the reference simulation is prescribed and only carbon emissions may change.

The effect of CO_2 fertilization over the period from preindustrial to present day (year 1850–2005) is strong for the modelled burned area (almost 20% difference in 2005) and even stronger for the carbon emissions in the PI_CO2 simulation (38% difference in 2005, Fig. 7). Using the burned area of the reference simulation (PI_CO2_BFref) the emissions still increase around 15%.

The effect of CO_2 fertilization on the fire carbon emissions is strongest in the regions that show frequent fire occurrence in the model simulations (Fig. 8).

However, the present knowledge on the magnitude of CO_2 fertilization is still very uncertain (Körner, 2006; Leuzinger and Hättenschwiler, 2013). Satellites observed an increase in green foliage cover in warm, arid environments over the last 30 years. When removing the effect of variations in precipitation, still an increase of 11% was found (Donohue et al., 2013). This increase is consistent with estimates of the effect of CO_2 fertilization based on plant gas exchange theory (Donohue et al., 2013). The regions where the effect of CO_2 fertilization is most important (dry and warm) are also the regions that are strongly affected by fire. This is consistent with our results with strongest effects on fire carbon emissions in regions with frequent fire occurrence. Strong impacts of CO_2 fertilization on the land carbon cycle have been found previously in a modelling study for the historical period since 1860 (Shevliakova et al., 2013). This study, however, did not investigate the effects on the fire carbon emissions. The effect of CO_2 on biomass burning for lower CO_2 concentrations in the past has been investigated by comparing the glacial and preindustrial period (Martin Calvo et al., 2014). The biomass burning flux during the last glacial maximum increased with a factor of 4–10 in simulations with preindustrial CO_2 concentration (280 ppm) compared to the simulation with the CO_2 concentration of the last glacial maximum (185 ppm). The absolute change in atmospheric CO_2 concentration is comparable to the change in our study (285 ppm–378 ppm), but as the effect of CO_2 to fertilization saturates a lower impact on fire carbon emissions in our study is expected. For future scenarios with higher CO_2 concentrations the effect on carbon emissions may therefore decrease.

4. Concluding summary

Bottom up wildfire emission inventories are usually based on a combination of burned area or fire count data and assumptions on available biomass. This approach does not take into account the temporal variation of fuel load and can only take into account a limited spatial variability, e.g. average fuel loads for a limited number of vegetation classes.

In this study we applied a vegetation model as a tool to investigate the influence of fuel variability on fire carbon emissions. We analyzed the influence of fuel seasonality on fire emissions for present day conditions. Fuel load thereby affects directly fuel consumption and the amount of wildfire emissions. In addition, fuel load controls the spread rate of a fire and thus the burned area, which in turn impacts the amount of fuel consumed during a fire event. In the model we can disentangle these two effects by either allowing the fuel load to impact the rate of spread or by prescribing a constant burned area. Allowing effects on burned area and carbon emissions mimics the potential error in approaches that assume a constant burned area per fire count. Other approaches that use burned area as input can only show effects of the fuel variability on the emissions.

Overall based on our land carbon cycle model we find small differences in global wildfire emissions when using mean fuel loads in time. For the simulation using a mean fuel load per grid cell that also impacts burned area (MEAN) the global carbon emissions are reduced globally by 1.74%. For the same simulation but using a prescribed burned area (MEAN_Bref) the differences are similar (1.66%). In both cases for all selected trace gases and aerosols the differences to the REF simulation are similar to the difference in total carbon emissions. This means that the influence of seasonal variations on fire emissions is low according to our model. Using maximum or minimum fuel loads leads to strong over (85%) and underestimations (45%) of carbon emissions, respectively. The

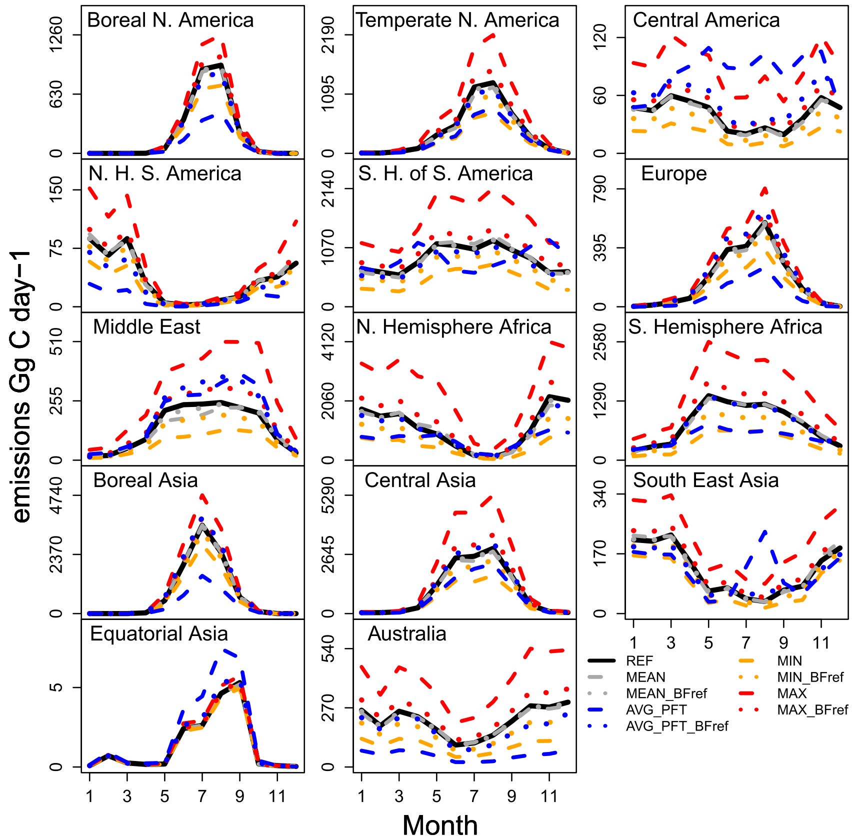

Fig. 6. Seasonality of carbon emissions for different regions, totals over regions in Gg C day^{-1}.

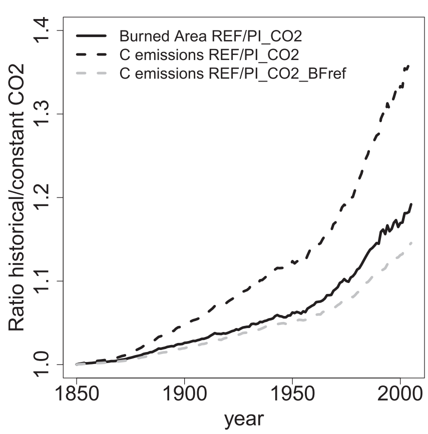

Fig. 7. Ratio of modelled global annual burned area and carbon emissions of the simulation REF to PI_CO2 and PI_CO2_BFref for the years 1850–2005.

effects are similar for all aerosols and trace gases considered here. The sensitivity of our model to minimum and maximum values shows that fuel limitation is an important factor in our model, which is in line with a number of studies (Archibald et al., 2009; Bradstock, 2010; Staver et al., 2011; Van Der Werf et al., 2008). The small differences to the reference in the simulation with mean fuel load per gridcell shows that the seasonality is of a minor importance and the mean fuel load is in general a good proxy.

For the simulation with mean fuel load for each plant functional type (AVG_PFT), in which within PFT variations of fuel load are not accounted for, the global total carbon emissions are 30% lower. We found large spatial differences, which result in different relative changes in emission estimates for trace gases and aerosols (39–22%). We therefore conclude that the spatial variation in fuel load is more important to account for in global emission estimates than its seasonal variation. Prescribed burned area strongly reduces the deviations from the reference in the MIN_BFref, MAX_BFref and AVG_PFT_BFref simulations. Using the burned area instead of fire counts in approaches estimating the fire emissions therefore can improve the quality of the estimates.

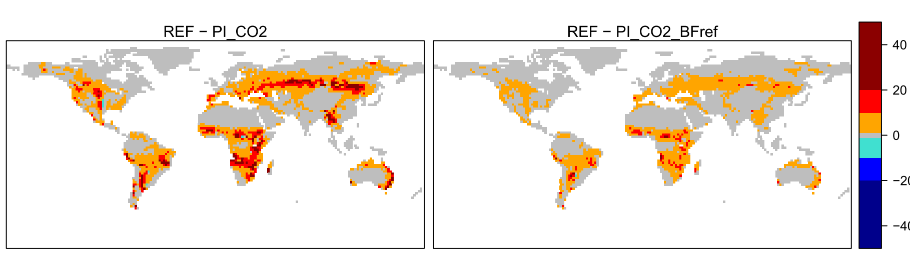

Fig. 8. Difference in carbon emissions between the REF and PI_CO2 simulation in gC m^{-2} year^{-1}.

Over the time period from 1850 to present day we found a strong effect of the CO_2 fertilization on burned area (20% increase in the year 2005) and carbon emissions (more than 35% in the year 2005). When prescribing the burned area of the reference simulation the difference between carbon emissions is less than 15%. Note here, however, that CO_2 fertilization has a highly uncertain response and is discussed controversially in literature. In addition CO_2 fertilization may affect the composition of vegetation, here a shift towards woody types is expected, which we do not account for in the model. This effect could dampen the response found in our study.

Overall our study does not suggest that static approaches, which lack the seasonal variation of fuel availability show strong biases in mean carbon emissions or the strength of the fire season. Approaches using biomass densities per plant functional type could be improved by accounting for the covariation of fuel load and climate in space. When extrapolating to the past with lower concentrations in atmospheric CO_2 without considering the potential reduction in vegetation productivity overestimation of the fire emissions is likely. Not considering the effect of CO_2 in studies extrapolating into the future with much higher atmospheric concentrations may underestimate future fire occurrence and emissions. We expect that this effect will be more and more dampened for future scenarios as the effect of CO_2 fertilization is likely limited by nutrient limitations which are not considered in our simulation. Nevertheless, current understanding suggests that the fertilization effect is strongest in dry regions where higher atmospheric CO_2 leads to a higher water use efficiency of vegetation. These dry regions are the regions with high fire emissions. Therefore this process should be considered for wildfire emission trends over decades or centuries.

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