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Supporting Online Material for

Fire in the Earth System

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Further details on data provided in Figure 1:

The qualitative schematic of global fire activity through time (Figure 1) is based upon Pre-Quaternary distribution of charcoal (*S1-3*), Quaternary and Holocene charcoal records (*S4*), and modern satellite observations (*S5*), in relation to percent atmospheric O_2 content (*S6, 7*), ppm of CO_2 (*S7-9*), appearance of certain vegetation types (*S10, 11*), and the presence of the genus *Homo* (*S12*).

Further details on data provided in Figure 3:

Radiative forcing is defined by the Intergovernmental Panel on Climate Change (IPCC) as the change in stratospherically adjusted radiative flux at the tropopause, compared to 1750AD (*S13*). Positive forcing will increase, while negative forcing will decrease, global mean surface temperature. Fires change radiative forcing through altered atmospheric composition and/or changes in surface albedo.(*S14-17*).

Assessing radiative forcing requires understanding fire extent and frequency in the pre-industrial era. Although pre-industrial fire rates were often assumed to be much lower than current rates, recent review of charcoal datasets around the world shows that rates have been declining since AD1 up to 1750AD, with several excursions during relatively warm or cold periods (*S18*). However, for some regions, this trend now appears to be reversing due to climate change (*S19*). Globally, we assume that current savanna and forest fire rates are not different now than they were pre-industrially, with the notable exception of extensive deforestation fires. For example, contemporary fires in peatlands of Southeast Asia are known to have increased over the past 50 years (*S20*). Thus, these collective tropical deforestation fires are the primary fire-related driver of radiative forcing. We assumed that all fire emissions (*S21*) from tropical forest regions (*S22*) were directly related to deforestation. We also assume peat fires in Southeast Asia are a direct consequence of deforestation and constitute a new anthropogenic emission source that was insignificant prior to 1750. We estimate that annual average tropical deforestation and peatland fires emit 0.65 Pg C ($P=10^{15}$, C = carbon) $year^{-1}$ with 32% originating from tropical America, 14% from Africa, and 54% from tropical Asia from 1997-2006 (*S21*). Emissions from tropical Asia are roughly split between the combustion of forest and peatlands.

Compiling best available, published information we estimate that fires have contributed up to about 19% of the anthropogenic radiative forcing since the pre-industrial era. This is a conservative estimate based on fire-related CO_2 emissions from deforestation fires; all other estimated terms cancel each other. These forcing estimates are highly uncertain and interdisciplinary research is needed to provide a more comprehensive estimate. Strikingly, however, fires influence 8 out of the IPCC's 13 identified radiative forcing terms.

Long-lived greenhouse gases: CO_2, CH_4, N_2O, and halocarbons

CO_2 levels have increased over the industrial era due to fossil fuel emissions and deforestation. It is difficult to estimate which fraction of these deforestation emissions was due to fires exclusively, versus decomposition of leftover plant material after logging or fire. Over the last decade, in regions that are experiencing high deforestation rates, fire emissions constitute approximately 50% of total deforestation carbon losses (*S21*), although this percentage is controversial and some authors estimate a larger (*S23*), or smaller (*S24*) contribution by fires. Given limited available global-scale information, we assume that fires contribute a constant 50% of total carbon emissions through time from deforestation.

Total fossil fuel emissions since 1750 were estimated at 315 Pg C (*S25*), while CO_2 emissions due to deforestation since 1750 were estimated at 182-199 Pg C (*S24*, *26*). Using these estimates, the relative contribution to CO_2 emissions from deforestation was 37-39%. Therefore, we estimate that 50% of deforestation CO_2 emissions is due to fires, or ~19% (half of the estimated 37-39% from above) of the total CO_2 radiative forcing. This is the estimated gross contribution. Deforested areas that convert back to forest act as a carbon sink (*S27*), and could lower the calculated fraction. It is unknown what fraction of historically cleared forests are regrowing. While we have assumed that there is a steady state in the emission and sequestration from all other fires, climate change may now be resulting in a net increase in emissions due to: (a) more severe fire weather (*S19*); and (b) reduced tree life spans due to drought stress (*S28*).

Building on our estimates of carbon losses and using published emission factors (*S29*, *30*), we estimate that methane (*CH_4*) emissions from deforestation and tropical peatland fires are 14 Tg year^{-1}. By comparison total contemporary CH_4 sources are ~600 Tg year^{-1} (*S31*-*33*), while pre-industrial sources were ~250 Tg year^{-1} (*S34*). If we assume that changes in CH_4 emissions are constant, then the contribution of fire to increased radiative forcing by CH_4 is approximately 4%. A more detailed quantification requires better knowledge of pre-industrial biomass burning emissions and other sources of CH_4 as well as their evolution through time (*S31*).

Following the same logic, deforestation and tropical peatland fire *N_2O* emissions are ~0.36 Tg N_2O year^{-1} (*S21*, *29*), compared to 8 Tg N_2O year^{-1} for all sources combined (*S13*). Assuming that the ratio between the different sources of increased N_2O emissions has been relatively constant in time, the contribution attributable to fire is ~5%. Here it is noteworthy to point out that N_2O emission factors are very poorly known, adding to the already large uncertainty

Fires do not emit *halocarbons* into the atmosphere.

Ozone

Fires represent an important source of *ozone* precursors such as NO_x, especially in tropical regions. The evolution of ozone sources through time and its radiative forcing is relatively well researched (*S35, 36*), but in these studies the contribution of fires was not determined. More recently, the radiative forcing of ozone generated by fire emissions has been estimated at 0.15 W m^{-2}, or 43% of the total radiative forcing of O_3 (*S37*). This estimate was based on fire emissions input datasets that assumed that about 5 Tg more NO_x $year^{-1}$ is emitted in contemporary times compared to pre-industrially. Deforestation and peat fires add about 2 Tg NO_x $year^{-1}$. As a very uncertain estimate we therefore assume that the fire component is 17%. Clearly, ozone is impacted by other factors than just NO_x and more work—including measuring NO_x emission factors over tropical peatlands—is needed to lower uncertainty.

Albedo

Compared to forests, croplands and natural grasslands have a long term cooling effect due to higher *albedo* that is partly attributable to fire, e.g., when burning causes deforestation or frequent fire is used to maintain a treeless condition. Burning may also cause short-term warming of the surface due to blackening (*S15, 38, 39*), or cooling of the surface due to post-fire changes in vegetation cover and increased exposure of snow cover at high latitudes (*S16, 40*). Here, we assume again that 50% of deforestation is due to fires, and since most of the negative forcing from increased albedo is related to deforested land, we assume that the fire contribution to this forcing is 50%.

Black carbon on snow warms the surface by decreasing albedo. At least 80% of black carbon forcing stems from fossil fuel and biofuel sources, but up to 20% can be attributed to fires (*S41*), which can affect high latitude regions. The northern hemisphere summer fire season may produce black carbon that affects areas that remain covered by snow and ice. This effect is well illustrated by the comparison between 1998 (a high fire year in the boreal, 0.054 W m^{-2}) and 2001 (a low fire year, 0.049 W m^{-2}). Since we have assumed that only deforestation fires have increased over time and black carbon on snow stems mostly from fires in boreal and temperate regions we therefore conclude that the net contribution of fire in changing surface albedo is zero. However, the rapid warming in boreal regions that is increasing fire activity may be increasing this radiative forcing term (*S42*).

Aerosols

The *direct aerosol effect* associated with light scattering sulphate aerosols generally has a cooling effect. Fires, however, only make a very minor contribution (2%) to this effect. In contrast, fires are an important source of black carbon that has a tropospheric warming effect. The total effect (average over models used in IPCC AR4 (*S13*)) has been estimated at +0.03 W m^{-2}, albeit much uncertainty remains. Estimates from the AEROCOM experiment, for example, ranged between -0.05 and 0.08 W m^{-2} based on nine different models (*S43*) with pre-industrial emission rates of about 20%. Deforestation and peatland fires contribute about a third of the global biomass burning black carbon emissions, and we thus assume that these fires have a 0.01 W m^{-2} radiative forcing due to black carbon.

In contrast to long-lived greenhouse gases the spatial and temporal distribution of black carbon emissions influences their effect on radiative forcing.

Aerosol particles emitted by fires also have profound impacts on clouds, an *indirect aerosol effect* (*S44, 45*). Smoke aerosols can increase or decrease cloud cover in complex and non-linear ways. There are two opposing effects of aerosols on clouds, the microphysical (cloud condensation nuclei) and radiative (black carbon). There is limited understanding of the interaction of these terms at the regional scale (*S45*). For example, in areas with heavy smoke pollution, there is a large increase in cloud condensation nuclei populations that decrease cloud droplet size resulting in increasing cloud lifetime and cloud albedo (*S46*). However, the large amount of black carbon in clouds near burning sources increases the susceptibility of low clouds to evaporation, inhibiting cloud formation and development (*S47*). This leads to a decrease in cloud cover in the presence of large amounts of absorbing aerosols. This effect is important for low clouds, but not very relevant for deep convective clouds in tropical regions. The smaller droplets also favor cloud development higher in the atmosphere.

In sum, at present it is not possible to present reliable estimates of the global indirect effects of aerosols in terms of radiative forcing. Regional studies indicate that smoke may both increase or decrease cloud cover and cloud height (*S48*), but currently no global scale study exists that has quantified these important effects.

Table S1: Seven examples of fire regimes that occur in different woody vegetation types and associated plant life history strategies and traits. Note, this table is not comprehensive and there are graduations between fire regimes.

Fire type	**Characteristic vegetation type**	**Climatic conditions**	**Fuel type**	**Fire frequency**	**Fire intensity**	**Fire stimulated recruitment** (establishes seedlings immediately post-fire)	**Crown sprouting** (replaces photosynthetic area following defoliation)	**Root suckering** (replaces fire-killed stems from existing root system)	**Self pruning of dead lower branches** (removes fuel ladders to inhibit canopy fire spread)	**Thick bark** (protects cambium)
Surface	Tropical rainforest	Severe drought	Leaf litter and soil organic matter	Very low	Low	Nil	Low	Moderate	Low	Low
Surface	Humid Tropical Savanna	Seasonal drought	Herbaceous	High	Low	Nil	High	High	High	High
Surface	Dry ponderosa pine forest, western USA	Drought with antecedent wet period	Stratified fuels including litter, twigs, shrubs	High	Low	Low	Low	Low	High	High
Surface	Dry eucalypt forest, Australia	Dry period with moderate fire weather	Stratified fuels including litter, twigs, shrubs	Medium	Moderate	Moderate	Low	Low	High	High
Crown	Fire-dependent Mediterranean shrublands	Drought, extreme dry weather and strong winds	Above ground woody biomass	Low	High	High	High	Low	Nil	Nil
Crown	High-elevation conifer forests, western USA	Extreme drought, and strong winds	Above ground woody biomass and organic soil layers	Low	High	High	High	Moderate	Nil	Low-Moderate
Crown	Wet eucalypt. forests, Australia	Drought, extreme dry weather and strong winds	Above ground woody biomass and organic soil layers	Low	High	High	Low	Low	High	Low

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