Supplement of Clim. Past, 15, 1885–1911, 2019
https://doi.org/10.5194/cp-15-1885-2019-supplement

Climate of the Past
Open Access

Supplement of

Effects of land use and anthropogenic aerosol emissions in the Roman Empire

Anina Gilgen et al.

Correspondence to: Anina Gilgen (anina.gilgen@env.ethz.ch) and Ulrike Lohmann (ulrike.lohmann@env.ethz.ch)

S1 Map of the Roman Empire

Fig. S1: The Roman Empire at its greatest extent (117 CE) with its vassals in pink. Adapted from Tataryn (2016); licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license (https://creativecommons.org/licenses/by-sa/3.0/deed.en).

S2 Model setup

Tab. S1: Greenhouse gas concentrations and orbital parameters. Precession is expressed as the longitude of the perihelion with respect to the equinox. The values are averages over 50 CE to 150 CE.

Var.	Unit	Value
CO_2	ppm	278
CH_4	ppb	662
N_2O	ppb	267
Eccentricity	-	0.01742
Precession	degrees	250.8
Obliquity	degrees	23.68

Tab. S2: Overview of natural fire aerosol, anthropogenic aerosol, and SOA precursor emissions in the different ECHAM-HAM-SALSA simulations. The multiplication factor refers to the natural fire emissions calculated with CBALONE-SPITFIRE. l stands for the fraction of the vegetated area that is covered by anthropogenic land (crop and pasture) and AA for anthropogenic aerosol emissions.

Simulation	Multiplication factor	AA	SOA precursor emissions
no_human	1	No	based only on natural land cover
LCC_HYDE	1	No	changed due to anthropogenic land cover
LCC_KK	1	No	changed due to anthropogenic land cover
LCC_HYDE_low	$(1-l)$	Yes	changed due to anthropogenic land cover
LCC_HYDE_int	$(1-l)$	Yes	changed due to anthropogenic land cover
LCC_KK_high	$(1-l)$	Yes	changed due to anthropogenic land cover

S3 Aerosol emission factors for fuel consumption

The fuel consumption studies that we considered mostly provide emission factors for either open fire places or traditional stoves. An exception is the measurement of olive pits that we included, which was conducted in a pellet stove; it was the only measurement of olive pits that we could find, and olive oil pressing waste was employed as a domestic and industrial fuel throughout Antiquity in the Mediterranean (Rowan, 2015).

S3.1 Wood

For wood combustion, we considered many wood types which were abundant in the Roman Empire (e.g. different types of oak, olive tree, maritime pine, or beech). However, many of these measurements were conducted with the same burning devices (Alves et al., 2011; Calvo et al., 2015; Fernandes et al., 2011). Looking at different studies, we observed that the differences in EFs between different wood types are sometimes smaller than the differences between different measurement setups. Hence, we also decided to include some trees in our compilation which were not present in the Mediterranean region (e.g. Lespedeza, Paulownia) to consider more independent studies. The medians and quartiles that were derived for the emission factors of wood (EF_{wood}) from the random sampling can be found in Table S3.

S3.2 Agricultural waste

For agricultural waste, a large variety of burning material was considered (e.g. wheat straw, rice straw, dung). Although the composition of agricultural residues in the Roman Empire differs from our compilation (e.g. rather Triticum dicoccum and barley instead of Triticum aestivum and rice; olive pits and chickpeas instead of peanuts and soybean residues), we assume that the emission factors are not fundamentally different: our compilation considers a large range of agricultural waste types. Furthermore, based on our compiled data, the measurement setup seems to be as important as the specific fuel type. The calculated medians and quartiles for the emission factors of agricultural waste (EF_{agri}) can be found in Table S4.

S3.3 Charcoal

Compared to wood and agricultural waste, only few studies estimated aerosol EFs for charcoal burning and charcoal making. Furthermore, most of them provide measurements of total suspended particles (e.g. Smith, 2000), and not for BC and OC. Thus, we considered only the very recent study by Keita et al. (2018) for BC and OC, who measured BC and OC for charcoal cooking fires and charcoal making in West Africa and calculated emission factors. Maybe even more important than knowing the exact BC and OC emission factors for charcoal burning is considering also the emissions from charcoal making. To produce 1 kg of charcoal, approximately 7 kg of wood are needed with traditional methods (Olson, 1991). As a consequence, using charcoal instead of wood as fuel might overall result in similar or even higher aerosol emissions, since for every kilogramme of charcoal burnt, the aerosols emitted during the production of this kilogramme of charcoal should also be considered. The aerosol emission factors per kilogramme of wood used for charcoal ($EF_{\mathrm{ch_w}}$) were therefore calculated as:

$$EF_{\mathrm{ch_w}} = \frac{1}{7} \cdot EF_{\mathrm{chb}} + EF_{\mathrm{chm}}, \tag{1}$$

where EF_{chb} is the emission factor for charcoal burning (per kilogramme of charcoal) and EF_{chm} is the emission factor for charcoal making (per kilogramme of wood). The emission factors for EF_{chb} and EF_{chm} can be found in Tables S5 and S6, respectively.

Considering that charcoal is often cited as almost smokeless (e.g. Wood and Baldwin, 1985; Lohri et al., 2016), the measured EF_{chb} of BC (median: $0.59\,\mathrm{g\,kg^{-1}}$; comparable to the burning of other types of biofuel) is relatively high – a discrepancy that already Bond et al. (2004) noted for the emission factors of total suspended particles. In the future, more measurements could help to better understand this inconsistency.

Inserting the estimates of EF_{chb} and EF_{chm} in the equation above results in $EF_{\mathrm{ch_w}}$ of $0.26\,\mathrm{g\ kg_{wood}^{-1}}$ (0.18, 0.39) for BC, $3.94\,\mathrm{g\ kg_{wood}^{-1}}$ (3.27, 4.80) for OC, and $0.21\,\mathrm{g\ kg_{wood}^{-1}}$ (0.14, 0.32) for SO_2.

S3.4 Combining different sectors

To assess the overall emission factor, we needed to estimate how much which sector contributed to the total fuel consumption. Except for SO_2, the emission factors are similar for wood and agricultural waste. The OC emission factors for charcoal burning and production (expressed as per kilogramme wood) are larger than for wood and agricultural waste, whereas the opposite is the case for BC. Thus, different assumptions concerning the contributions from the three sectors would affect the BC to OC ratio, rather than the emissions of both of them.

Wood fuel (including wood for charcoal making) was the dominant fuel in the Roman Empire (Olson, 1991). However, agricultural residues such as chaff, olive pits, and dung were also used, most evidently in regions lacking in supplies of wood (e.g. Roman North Africa and Roman East; Mietz, 2016; Rowan, 2015). In developing countries in 1985, the mass contribution of agricultural waste to total biofuel combustion (excluding burning in fields) ranges from 14% in Africa to over 40% in Asia (Yevich and Logan, 2003). Based on these numbers, we assumed that 20% of the used fuel consisted of agricultural waste.

Like for developing countries (Wood and Baldwin, 1985; Yevich and Logan, 2003; Lohri et al., 2016), the use of charcoal was especially important in urban areas in ancient times (Veal, 2017). Veal (2017) assumes that in the cities “perhaps 80%” of the burnt fuel consisted of charcoal with the remainder being wood, whereas the opposite ratio occurred in rural areas. In her two extreme case scenarios for Rome, she used charcoal contributions of 80% and 20% to total fuel. Assuming a conversion factor of 7, this means that 97% and 64% of the wood fuel was used for charcoal making, respectively.

These estimates are higher than present-day estimates in countries where charcoal is produced: using data from the food and agricultural organisation (FAO[1]), we calculated the contribution of charcoal production to total wood fuel production. We chose the year 1970, when fossil fuels were likely (even) less common in developing countries than today. A factor of 6 was used[2] to convert the weight of charcoal (metric tonnes) to the volume of wood ($\mathrm{m^3}$) required to make the specified charcoal weight. It is unclear whether countries include the amount of wood used for charcoal making in the woodfuel statistics which they report to FAO[3]. To account for the fact that the data might be inconsistent, we used two methods (DIV1 and DIV2) to calculate

[1] `http://www.fao.org/faostat/en/#data/FO`, downloaded: 18 August 2018

[2] `http://www.fao.org/docrep/005/y4450e/y4450e13.htm`, last access: 27 November 2018; a similar value of 7 is mentioned here: `http://www.fao.org/docrep/x5667e/x5667e04.htm`, last access: 17 Januar 2019

[3] http://www.fao.org/docrep/005/y4450e/y4450e13.htm

the contribution of charcoal to wood fuel ($frac_{\mathrm{DIV1}}$ and $frac_{\mathrm{DIV2}}$):

$$frac_{\mathrm{DIV1}} = \frac{Wood_{\mathrm{ch}}}{Wood_{\mathrm{con}} + Wood_{\mathrm{noncon}}} \tag{2}$$

and

$$frac_{\mathrm{DIV2}} = \frac{Wood_{\mathrm{ch}}}{Wood_{\mathrm{ch}} + Wood_{\mathrm{con}} + Wood_{\mathrm{noncon}}}, \tag{3}$$

where $Wood_{\mathrm{ch}}$ stands for the production of wood used for charcoal making, $Wood_{\mathrm{con}}$ for the production of coniferous fuel wood, and $Wood_{\mathrm{noncon}}$ for the production of non-coniferous fuel wood. With method DIV1, we arrive at values above 100% for some countries. Since this makes no sense, we cap these values at 100%.

We calculated the mean and the median fractions for both the world and Africa, the latter having the largest per capita use of charcoal in the developing world (Yevich and Logan, 2003). For both cases, we excluded all countries that do not produce charcoal, i.e. mainly developed countries that predominantly use fossil fuels. The values are shown in Table S7. The values lie in a relatively narrow range between 13% and 25%. Although the large majority of people living in developing countries mainly used biomass for domestic energy (Wood and Baldwin, 1985), it is possible that the use of fossil fuels might affect our estimates to some degree.

Overall, the FAO data shows lower contributions of charcoal to total fuel wood than the estimates by Veal (2017). This could indicate that the estimates by Veal (2017) are too high for the whole Roman Empire (which was not the target of her study), since the Empire consisted of many parts that differed considerably with respect to wood supply. However, the Roman Empire had a high urbanisation rate (≈ 10 %, with higher values in Italy; Temin, 2006) and metallurgy was important (Harris, 2013), which speakes for a potentially higher contribution of charcoal than under present-day conditions. In the end, we decided to use a fraction of 50% of charcoal wood to total fuel wood, which is a compromise between the estimates by Veal (2017) and the FAO based values. To summarise, we assume that 20% of the fuel consisted of agricultural waste, 40% of charcoal (in terms of wood needed for charcoal production), and 40% of wood.

Tab. S3: Aerosol emission factors for wood burning (EF_{wood}) in $\mathrm{g\,kg^{-1}}$ used for the low, the intermediate, and the high scenarios.

	Low estimate	Intermediate estimate	High estimate
BC	0.27	0.42	0.65
OC	0.84	2.09	4.15
SO_2	0.0021	0.098	0.20

Tab. S4: Aerosol emission factors for agricultural waste burning (as fuel; EF_{agri}) in $\mathrm{g\,kg^{-1}}$ used for the low, the intermediate, and the high scenarios.

	Low estimate	Intermediate estimate	High estimate
BC	0.25	0.45	0.85
OC	1.16	2.40	4.32
SO_2	0.0082	0.022	0.050

Tab. S5: Aerosol emission factors for charcoal burning (EF_{chb}) in $\mathrm{g\,kg^{-1}}$ (per kg charcoal) used for the low, the intermediate, and the high scenarios.

	Low estimate	Intermediate estimate	High estimate
BC	0.44	0.59	0.79
OC	0.45	0.96	2.03
SO_2	0.29	0.43	0.62

Tab. S6: Aerosol emission factors for charcoal production (EF_{chm}) in $\mathrm{g\,kg^{-1}}$ (per kg wood) used for the low, the intermediate, and the high scenarios.

	Low estimate	Intermediate estimate	High estimate
BC	0.11	0.18	0.28
OC	3.21	3.81	4.51
SO_2	0.10	0.15	0.23

Tab. S7: The percentages of wood used for charcoal making to total fuel wood. Two different methods (DIV1 and DIV2) were applied. Data was taken from FAO (year 1970).

Method	World, mean	World, median	Africa, mean	Africa, median
$frac_{\mathrm{DIV1}}$	25%	16%	24%	16%
$frac_{\mathrm{DIV2}}$	18%	13%	18%	14%

S4 Estimating crop yield Y

The agronomist Columella stated that the seed-yield ratios for most parts of Italy were seldom above 4:1 in the first century CE (Spurr, 1986). Assuming a sowing amount of $135\,\mathrm{kg\,ha^{-1}}$ (advocated by the agronomists as a typical sowing amount; Goodchild, 2007), a ratio of 4:1 results in yields of $540\,\mathrm{kg\,ha^{-1}}$. This yield is quite low compared to other sources, which show that yields of 5:1 and 6:1 were the most frequent in Italy and higher yields of 10-15:1 were not infrequent (Goodchild, 2007). For some regions, Varro (who lived in the first century BC) and Pliny the Elder (first century CE) reported even yields of 100:1 (Sinclair, 1998). So far, the estimates referred to Italy alone, but the variability between different Mediterranean countries was of course large: around 1921-1930 CE the average yields according to Hopkins (2017) ranged from values below $600\,\mathrm{kg\,ha^{-1}}$ (Cyrenaica, Tunisia, Algeria), through values between 600 and $1000\,\mathrm{kg\,ha^{-1}}$ (Greece, Portugal, Cyprus, Syria and Lebanon, Turkey, Spain) up to values above $1000\,\mathrm{kg\,ha^{-1}}$ (Bulgaria, Yugoslavia, Italy, France, Egypt). Overall, we concluded that yields representative for the whole Roman Empire roughly lie in the range between $500\,\mathrm{kg\,ha^{-1}}$ and $1000\,\mathrm{kg\,ha^{-1}}$.

S5 Seasonal impact of anthropogenic land cover change

Tab. S8: Absolute values of the reference simulation no_human ("no") and the simulation LCC_HYDE ("H") for each season (JJA=summer, SON=autumn, DJF=winter, and MAM=spring) and the whole year: cloud droplet number concentration burden, liquid water path, cloud cover, cloud radiative effect, wind velocity at 10 m altitude, surface albedo over land, evaporative fraction, and turbulent flux. The values are averaged from 10° W to 50° E, 20° N to 60° N. Relative changes are shown in brackets and the stars indicate significant changes (5% significance level; $N = 20$).

Var.	Unit	no JJA	H JJA	no SON	H SON	no DJF	H DJF	no MAM	H MAM	no year	H year
CDNC	10^9 m^{-2}	31.46	30.54 (−2.9%)	27.12	25.66 (−5.4%)	12.85	13.19 (2.6%)	22.49	21.92 (−2.5%)	23.52	22.87 (−2.8%)
LWP	g m^{-2}	54.96	54.89 (−0.1%)	59.03	56.36 (−4.5%)	39.22	39.10 (−0.3%)	41.49	40.13 (−3.3%)	48.69	47.64 (−2.2%)
CC	-	0.32	0.31 (−3.1%)	0.50	0.51 (2.1%)	0.58	0.58 (1.2%)	0.54	0.54 (−0.7%)	0.48	0.48 (0.2%)
CRE	W m^{-2}	−22.44	−22.58 (0.6%)	−4.23	−2.91 (−31.1%)*	4.57	4.60 (0.5%)	−14.43	−14.12 (−2.1%)	−9.21	−8.83 (−4.1%)
$Wind_{10}$	m s^{-1}	4.02	4.05 (0.8%)	4.09	4.14 (1.1%)	4.63	4.66 (0.6%)	4.33	4.37 (1.1%)	4.27	4.30 (0.9%)*
Albedo	-	0.26	0.26 (0.2%)*	0.25	0.25 (−0.0%)	0.26	0.26 (−0.3%)	0.25	0.25 (−0.2%)	0.26	0.26 (−0.1%)
Evap_frac	-	0.36	0.36 (−1.2%)	0.32	0.33 (0.8%)	0.32	0.33 (3.2%)*	0.43	0.43 (0.7%)	0.36	0.36 (0.8%)
F_{turb}	W m^{-2}	90.23	89.66 (−0.6%)	64.62	64.80 (0.3%)	52.26	52.73 (0.9%)	79.54	79.98 (0.5%)	71.78	71.91 (0.2%)

Tab. S9: The same as Table S8 but for the simulations no_human and LCC_KK ("KK").

Var.	Unit	no JJA	KK JJA	no SON	KK SON	no DJF	KK DJF	no MAM	KK MAM	no year	KK year
CDNC	10^9 m^{-2}	31.46	29.84 (−5.2%)	27.12	25.51 (−5.9%)*	12.85	11.73 (−8.7%)*	22.49	20.36 (−9.5%)*	23.52	21.90 (−6.9%)*
LWP	g m^{-2}	54.96	53.48 (−2.7%)	59.03	55.95 (−5.2%)*	39.22	36.07 (−8.1%)*	41.49	37.96 (−8.5%)*	48.69	45.89 (−5.8%)*
CC	-	0.32	0.31 (−1.7%)	0.50	0.50 (1.3%)	0.58	0.58 (0.1%)	0.54	0.53 (−1.5%)	0.48	0.48 (−0.3%)
CRE	W m^{-2}	−22.44	−22.20 (−1.1%)	−4.23	−3.13 (−25.8%)*	4.57	4.59 (0.4%)	−14.43	−13.28 (−8.0%)*	−9.21	−8.58 (−6.8%)*
$Wind_{10}$	m s^{-1}	4.02	4.18 (3.9%)*	4.09	4.22 (3.2%)*	4.63	4.74 (2.4%)*	4.33	4.49 (3.7%)*	4.27	4.41 (3.3%)*
Albedo	-	0.26	0.26 (0.8%)*	0.25	0.25 (0.2%)	0.26	0.26 (0.0%)	0.25	0.25 (−0.5%)*	0.26	0.26 (0.1%)
Evap_frac	-	0.36	0.36 (1.1%)	0.32	0.33 (1.3%)	0.32	0.33 (3.9%)*	0.43	0.43 (0.6%)	0.36	0.36 (1.6%)*
F_{turb}	W m^{-2}	90.23	90.20 (−0.0%)	64.62	64.13 (−0.8%)	52.26	52.30 (0.1%)	79.54	80.87 (1.7%)	71.78	71.99 (0.3%)

S6 OC and SO_2 emissions from anthropogenic sources and natural fire emissions around 100 CE

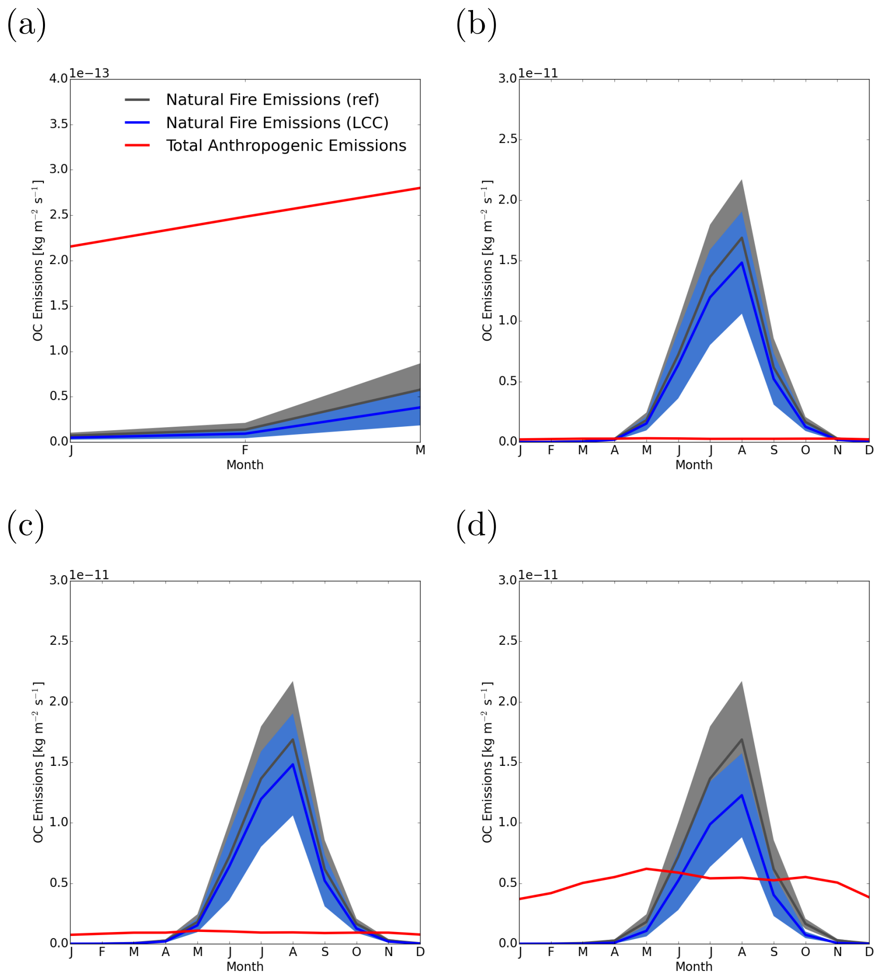

Fig. S2: The same as Fig. 4 in the manuscript but for OC instead of BC.

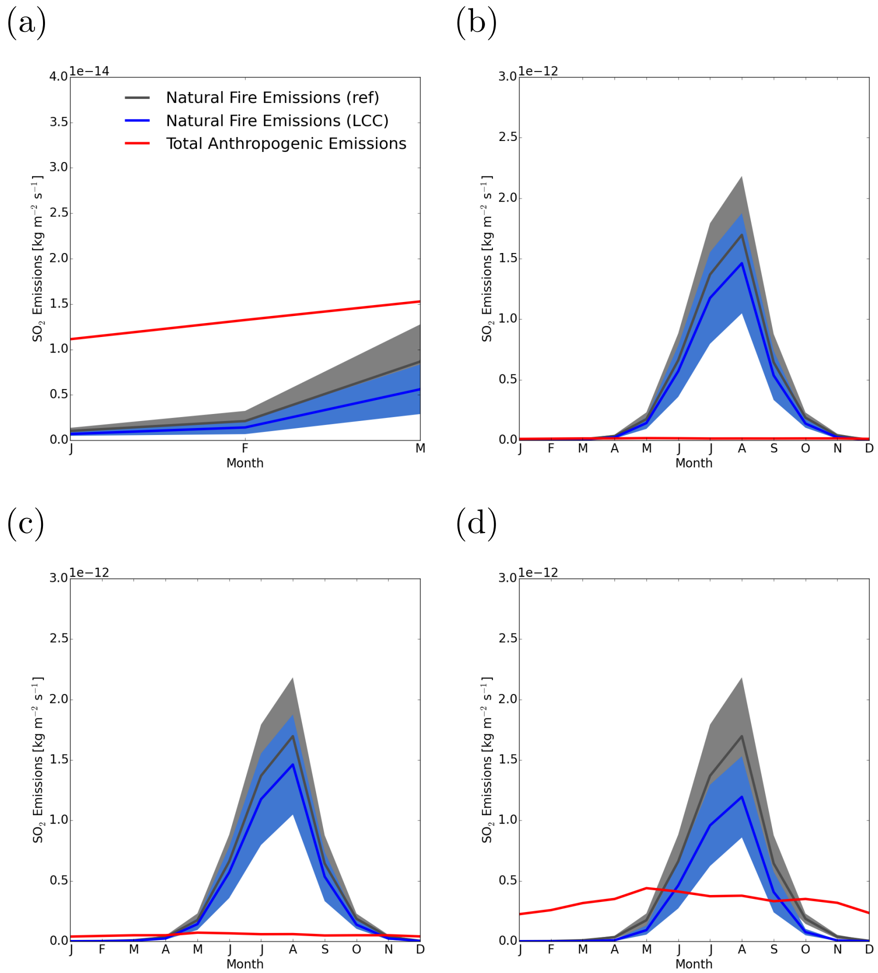

Fig. S3: The same as Fig. 4 in the manuscript but for SO_2 instead of BC.

S7 Seasonal impact of anthropogenic aerosol emissions

Tab. S10: Absolute values of the simulation LCC_HYDE and the simulation LCC_HYDE_low ("low") for each season (JJA=summer, SON=autumn, DJF=winter, and MAM=spring) and the whole year for the following variables: black carbon burden, organic matter burden, SO_4 burden, cloud droplet number concentration burden, liquid water path, cloud cover, aerosol radiative effect, and cloud radiative effect. The values are averaged from 10° W to 50° E, 20° N to 60° N. Relative changes are shown in brackets and the stars indicate significant changes (5% significance level; $N = 20$).

Var.	Unit	H JJA	low JJA	H SON	low SON	H DJF	low DJF	H MAM	low MAM	H year	low year
BC burden	µg m^{-2}	538.37	437.39 (−18.8%)*	170.43	141.04 (−17.2%)*	2.72	5.70 (109.7%)*	26.46	26.55 (0.3%)	185.42	153.43 (−17.3%)*
OM burden	µg m^{-2}	10151.91	8701.79 (−14.3%)*	3320.51	3051.25 (−8.1%)*	677.58	680.64 (0.5%)	1242.32	1254.44 (1.0%)	3865.01	3436.56 (−11.1%)*
SO_4 burden	µg m^{-2}	6331.80	6055.52 (−4.4%)*	4569.16	4596.97 (0.6%)	2600.15	2691.03 (3.5%)	3733.66	3680.67 (−1.4%)	4316.42	4262.86 (−1.2%)
CDNC	10^9 m^{-2}	30.54	32.02 (4.8%)	25.66	30.26 (17.9%)*	13.19	17.62 (33.6%)*	21.92	24.45 (11.5%)*	22.87	26.12 (14.2%)*
LWP	g m^{-2}	54.89	56.06 (2.1%)	56.36	67.22 (19.3%)*	39.10	56.95 (45.7%)*	40.13	46.66 (16.3%)*	47.64	56.69 (19.0%)*
CC	-	0.31	0.32 (4.0%)*	0.51	0.51 (1.5%)	0.58	0.60 (3.1%)*	0.54	0.55 (2.5%)*	0.48	0.50 (2.7%)*
ARE	W m^{-2}	−0.81	−0.76 (−5.9%)	−0.94	−0.95 (1.5%)	−0.51	−0.47 (−6.8%)*	−0.40	−0.22 (−43.2%)*	−0.66	−0.60 (−9.0%)*
CRE	W m^{-2}	−22.58	−22.78 (0.9%)	−2.91	−4.96 (70.3%)*	4.60	1.45 (−68.5%)*	−14.12	−17.20 (21.8%)*	−8.83	−10.95 (23.9%)*

Tab. S11: The same as Table S10 but showing results for the simulations LCC_HYDE_int ("int") and LCC_HYDE.

Var.	Unit	H JJA	int JJA	H SON	int SON	H DJF	int DJF	H MAM	int MAM	H year	int year
BC burden	µg m^{-2}	538.37	454.27 (−15.6%)*	170.43	153.68 (−9.8%)*	2.72	14.93 (448.8%)*	26.46	44.12 (66.7%)*	185.42	167.54 (−9.6%)*
OM burden	µg m^{-2}	10151.91	8781.79 (−13.5%)*	3320.51	3180.92 (−4.2%)	677.58	850.66 (25.5%)*	1242.32	1516.03 (22.0%)*	3865.01	3596.95 (−6.9%)*
SO_4 burden	µg m^{-2}	6331.80	6067.79 (−4.2%)	4569.16	4613.68 (1.0%)	2600.15	2682.92 (3.2%)	3733.66	3682.05 (−1.4%)	4316.42	4268.40 (−1.1%)
CDNC	10^9 m^{-2}	30.54	34.60 (13.3%)*	25.66	36.36 (41.7%)*	13.19	29.18 (121.2%)*	21.92	30.86 (40.8%)*	22.87	32.76 (43.2%)*
LWP	g m^{-2}	54.89	58.96 (7.4%)*	56.36	76.20 (35.2%)*	39.10	77.44 (98.1%)*	40.13	55.60 (38.5%)*	47.64	66.97 (40.6%)*
CC	-	0.31	0.32 (3.8%)	0.51	0.53 (3.9%)	0.58	0.62 (6.1%)*	0.54	0.55 (2.7%)*	0.48	0.50 (4.2%)*
ARE	W m^{-2}	−0.81	−0.79 (−2.8%)	−0.94	−0.92 (−2.1%)	−0.51	−0.43 (−16.3%)*	−0.40	−0.05 (−88.6%)*	−0.66	−0.54 (−18.0%)*
CRE	W m^{-2}	−22.58	−24.12 (6.9%)*	−2.91	−5.96 (104.7%)*	4.60	−0.86 (−118.7%)*	−14.12	−20.77 (47.1%)*	−8.83	−13.01 (47.2%)*

Tab. S12: The same as Table S10 but showing results for LCC_KK and LCC_KK_high ("high").

Var.	Unit	KK JJA	high JJA		KK SON	high SON		KK DJF	high DJF		KK MAM	high MAM		KK year	high year	
BC burden	µg m^{-2}	516.73	520.93	(0.8%)	169.10	233.65	(38.2%)*	2.67	70.53	(2542.2%)*	26.37	131.05	(397.0%)*	179.61	239.89	(33.6%)*
OM burden	µg m^{-2}	9466.62	9534.91	(0.7%)	3210.24	4332.61	(35.0%)*	623.35	1600.17	(156.7%)*	1145.62	2634.95	(130.0%)*	3627.28	4540.62	(25.2%)*
SO_4 burden	µg m^{-2}	6280.78	6065.80	(−3.4%)	4646.45	4765.02	(2.6%)	2566.28	2820.00	(9.9%)*	3699.46	3729.81	(0.8%)	4305.81	4351.47	(1.1%)
CDNC	10^9 m^{-2}	29.84	42.75	(43.3%)*	25.51	62.60	(145.4%)*	11.73	67.39	(474.5%)*	20.36	60.85	(198.8%)*	21.90	58.34	(166.4%)*
LWP	g m^{-2}	53.48	63.23	(18.2%)*	55.95	91.92	(64.3%)*	36.07	106.09	(194.2%)*	37.96	77.16	(103.3%)*	45.89	84.47	(84.1%)*
CC	-	0.31	0.33	(6.6%)*	0.50	0.54	(7.6%)*	0.58	0.64	(10.7%)*	0.53	0.58	(8.8%)*	0.48	0.52	(8.7%)*
ARE	W m^{-2}	−0.68	−0.81	(19.9%)	−1.00	−0.97	(−2.9%)	−0.51	−0.40	(−21.5%)*	−0.37	0.10	(−127.3%)*	−0.64	−0.52	(−18.7%)*
CRE	W m^{-2}	−22.20	−25.29	(13.9%)*	−3.13	−7.21	(130.0%)*	4.59	−4.33	(−194.3%)*	−13.28	−27.69	(108.5%)*	−8.58	−16.21	(88.9%)*

S8 Fixed SSTs versus MLO

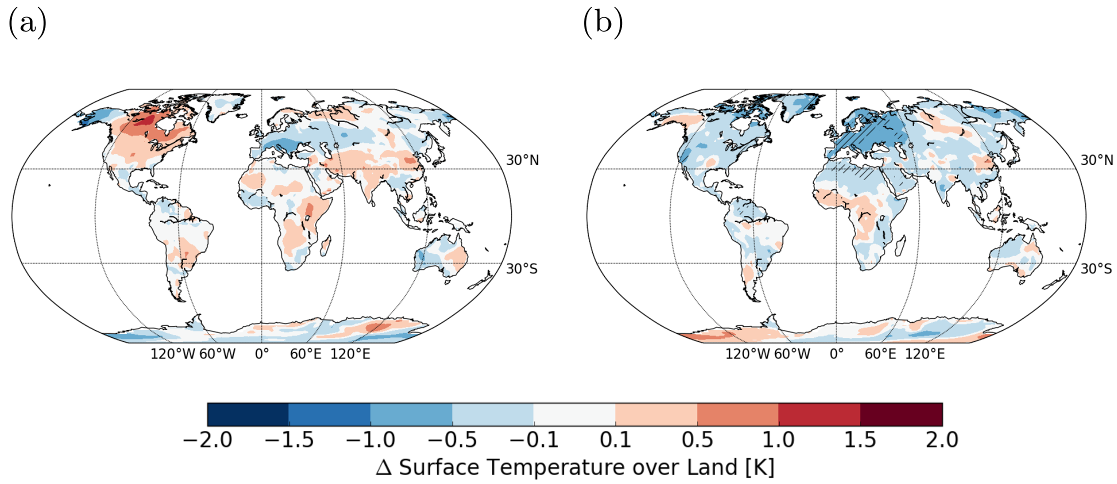

Fig. S4: The impact of anthropogenic land cover and aerosol emissions on land surface temperature for the intermediate emission scenario (difference between LCC_HYDE_int and no_human). Shown are changes simulated with fixed SSTs (a) and changes simulated with an MLO (b).

S9 Comparison between CBALONE-SPITFIRE emissions and emissions by van Marle et al. (2017)

Here, we compare the CBALONE-SPITFIRE emissions around 1835 CE with the emissions of van Marle et al. (2017) around 1835 CE, which could show biases in the fire model. The reconstructed emissions by van Marle et al. (2017) are used as input for simulations in the context of the Climate Model Intercomparison Project phase 6; we therefore call them "CMIP6 emissions" in the following. The CMIP6 emissions were calculated by merging satellite data with proxies for biomass burning (e.g. charcoal records and visibility observations) next to using the average of six fire models. The emissions simulated by CBALONE-SPITFIRE are not totally independent of the CMIP6 emissions because 3 of the 6 models considered by van Marle et al. (2017) include SPITFIRE (one of them was JSBACH-SPITFIRE).

The global averages of the fire emissions are relatively similar between CBALONE-SPITFIRE and CMIP6 around 1835 CE (Table S13). The values are somewhat larger for CBALONE-SPITFIRE, namely a factor of 1.2 for SO_2 and a factor of 1.7 for BC and OC emissions. However, one should keep in mind that the fire emissions by CMIP6 are not the truth and also uncertain. For example, Hamilton et al. (2018) concluded that the CMIP6 pre-industrial fire emissions are likely underestimated.

Although global averages are similar, CBALONE-SPITFIRE simulates pronouncedly higher aerosol emissions compared to CMIP6 in our study domain around 1835 CE (Tables S14, S15, S16). The disagreement is larger in summer and autumn (CBALONE-SPITFIRE 7 to 15 times higher) than in winter and spring (CBALONE-SPITFIRE 2 to 4 times higher). Furthermore, the fire emissions in winter are more located to the South in CBALONE-SPITFIRE; it simulates basically no fires in Eastern Europe in contrast to CMIP6, but higher emissions in North Africa and the Middle East (not shown). Note that the majority ($\approx 80\,\%$ in 1850 CE) of the

CMIP6 fire emissions in the study domain originates from agricultural crop waste burning on field, whereas crop area is excluded from burning in CBALONE-SPITFIRE. The CBALONE-SPITFIRE emissions could differ from the CMIP6 emissions over Europe because the first are only model-based, while the latter also include observational data. Furthermore, the models considered by van Marle et al. (2017) were driven by different forcing data than our CBALONE-SPITFIRE simulations.

Overall, the fire emissions calculated with CBALONE-SPITFIRE are higher than the CMIP6 emissions in the study domain around 1835 CE. As a consequence, the natural fire emissions calculated for 100 CE could be overestimated in the study domain.

Tab. S13: Global mean fire emissions (in 10^{-14} $\mathrm{kg\,m^{-2}\,s^{-1}}$) around 1835 CE used for CMIP6 and those calculated with CBALONE-SPITFIRE ("CBAL-SPIT"). The data covers 20 years around 1835 CE (1823-1842 CE).

	CMIP6	CBAL-SPIT
BC	10.0	17.0
OC	84.6	141
SO_2	12.5	14.5

Tab. S14: Mean BC fire emissions (in 10^{-14} $\mathrm{kg\,m^{-2}\,s^{-1}}$) averaged from 10° W to 50° E, 20° N to 60° N used for CMIP6 and those calculated with CBALONE-SPITFIRE ("CBAL-SPIT"). The data covers 20 years around 1835 CE (1823-1842 CE).

	CMIP6 1835 CE	CBAL-SPIT 1835 CE	CBAL-SPIT 100 CE
Autumn	6.65	62.4	33.9
Winter	0.470	1.95	0.339
Spring	6.29	16.7	9.20
Summer	14.8	135	142

Tab. S15: The same as Table S14 but for OC and in 10^{-13} $\mathrm{kg\,m^{-2}\,s^{-1}}$.

	CMIP6 1835 CE	CBAL-SPIT 1835 CE	CBAL-SPIT 100 CE
Autumn	2.80	43.0	26.9
Winter	0.295	1.07	0.178
Spring	3.39	11.1	7.14
Summer	6.77	101	126

Tab. S16: The same as Table S14 but for SO_2 (in 10^{-14} $\mathrm{kg\,m^{-2}\,s^{-1}}$).

	CMIP6 1835 CE	CBAL-SPIT 1835 CE	CBAL-SPIT 100 CE
Autumn	4.54	40.2	28.8
Winter	0.435	1.57	0.250
Spring	5.06	10.2	7.27
Summer	10.8	78.7	125

Comparing the two CBALONE-SPITFIRE simulations (1835 CE versus 100 CE; Tables S14, S15, S16) reveals that emissions around 1835 CE were somewhat lower in summer compared to 100 CE. However, for the other seasons, the emissions in 1835 CE are higher, especially in winter (a factor of 6). The differences can partly be explained by the differences in the population density; for 100 CE, only natural fires were calculated and the population density was thus set to 0 (Sect. 2.4). In the model, population shortens the fire duration but at the same time increases the number of ignition events. While the first effect dominates in summer, the second one dominates in the other seasons. Furthermore, differences in anthropogenic land cover (none assumed for 100 CE), natural vegetation, and climate can also contribute to the differences between 1835 CE and 100 CE.

S10 Emission factors considered for calculation

Tab. S17: Compilation of emission factors from burning: wood as fuel (key 1), agricultural residue as fuel (key 2), agricultural residue in the field (key 3), pasture or grass (key 4), charcoal (key 5), and wood for charcoal production (key 6). N stands for the number of samples, and "a" in the last column indicates for which measurements we estimated the standard deviation ("std"). The values are given in $g\,kg^{-1}$ on a dry matter basis. In this table, we show for simplicity four decimal places for all measurement, but this does not mean that all measurements had this precision.

Burning material	OC		BC		SO_2		N	Reference	Burning/ measurement device	Key
	average	std	average	std	average	std				
UP dung	7.1970	6.7530	0.5657	0.4949			7	Pandey et al. (2017)	traditional cooking-stove, India	2
Bihar dung	10.6500	10.0300	0.9700	0.8403			6	Pandey et al. (2017)	traditional cooking-stove, India	2
Chh rice straw	7.0786	5.1236	1.1157	1.3508			7	Pandey et al. (2017)	traditional cooking-stove, India	2
Chh tur stalk	8.0880	6.1330	1.9580	1.8140			10	Pandey et al. (2017)	traditional cooking-stove, India	2
Punjab wood	2.6000	2.3780	0.6750	0.4387			4	Pandey et al. (2017)	traditional cooking-stove, India	1
Raj wood	5.4041	5.0848	1.1410	1.0134			17	Pandey et al. (2017)	traditional cooking-stove, India	1
UP wood	2.1363	1.1830	0.5500	0.3464			8	Pandey et al. (2017)	traditional cooking-stove, India	1
AP wood	5.0125	3.6248	0.4550	0.2664			4	Pandey et al. (2017)	traditional cooking-stove, India	1
wheat straw	3.4600	2.0500	0.4200	0.2300	0.0400	0.0400	8	Cao et al. (2008)	combustion tower (simulating cooking in traditional stoves)	2
rice straw	2.0100	0.6700	0.4900	0.2100	0.1800	0.3100	14	Cao et al. (2008)	combustion tower (simulating cooking in traditional stoves)	2

corn stover	2.2500	0.7400	0.9500	1.0800	0.0400	0.0400	9	Cao et al. (2008)	combustion tower (simulating cooking in traditional stoves)	2
cotton stalk	1.8300	0.5400	0.8200	0.2000			2	Cao et al. (2008)	combustion tower (simulating cooking in traditional stoves)	2
rice straw	0.9000	0.4500	0.4600	0.2300			7	Turn et al. (1997)	wind tunnel	3a
wheat straw	2.1000	1.0500	0.7900	0.3950			2	Turn et al. (1997)	wind tunnel	3a
barley straw	3.0000	1.5000	1.2000	0.6000			2	Turn et al. (1997)	wind tunnel	3a
corn stover	1.7000	0.8500	0.6700	0.3350			2	Turn et al. (1997)	wind tunnel	3a
sugar cane	1.5000	0.7500	0.5900	0.2950			3	Turn et al. (1997)	wind tunnel	3a
wheat straw	2.8130	0.1470	0.6760	0.0270			4	Li et al. (2017)	combustion stove to simulate open burning	3
corn straw	2.3930	0.3510	0.7780	0.1520			4	Li et al. (2017)	combustion stove to simulate open burning	3
rice straw	6.8820	0.6890	2.1820	0.2780			4	Li et al. (2017)	combustion stove to simulate open burning	3
cotton residue	7.4150	0.5470	1.1920	0.1710			4	Li et al. (2017)	combustion stove to simulate open burning	3
soybean residue	1.5390	0.2530	0.6140	0.1900			4	Li et al. (2017)	combustion stove to simulate open burning	3
Maize-brick					0.0163	0.0104	3	Zhang et al. (2000)	brick stove with flue	2
Wood-India					0.0024	0.0024	3	Zhang et al. (2000)	metal stove without flue (from India)	1
Wheat-brick					0.0335	0.0174	3	Zhang et al. (2000)	brick stove with flue	2
Brush-brick					0.0056	0.0077	3	Zhang et al. (2000)	brick stove with flue	2
Brush-India					0.0025	0.0044	3	Zhang et al. (2000)	metal stove without flue (from India)	2

fireplace, softwood	3.0073	0.3335	0.7742	0.0697			3	McDonald et al. (2000)	heatilator model E36 fireplace	1
fireplace, hardwood	3.5800	0.7981	0.3975	0.1177			3	McDonald et al. (2000)	heatilator model E36 fireplace	1
wood stove, hardwood	2.8211	1.7706	0.3563	0.2169			3	McDonald et al. (2000)	noncatalytic Pineridge applicance	1
maritime pine	6.1344	3.0672	1.0650	0.5325			3	Alves et al. (2011)	traditional Portuguese brick open fireplace	1a
eucalypt	8.7264	4.3632	0.4444	0.2222			3	Alves et al. (2011)	traditional Portuguese brick open fireplace	1a
cork oak	6.9412	3.4706	0.3484	0.1742			3	Alves et al. (2011)	traditional Portuguese brick open fireplace	1a
golden wattle	3.8700	1.9350	0.6600	0.3300			3	Alves et al. (2011)	traditional Portuguese brick open fireplace	1a
olive	4.8015	2.4008	0.4158	0.2079			3	Alves et al. (2011)	traditional Portuguese brick open fireplace	1a
Portugese oak	9.1680	4.5840	0.4775	0.2388			3	Alves et al. (2011)	traditional Portuguese brick open fireplace	1a
holm oak	8.4800	4.2400	0.3520	0.1760			3	Alves et al. (2011)	traditional Portuguese brick open fireplace	1a
maritime pine	8.0196	4.0098	0.6357	0.3179			3	Alves et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1a
eucalypt	3.2160	1.6080	0.2479	0.1240			3	Alves et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1a
cork oak	8.0936	4.0468	0.2869	0.1435			3	Alves et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1a
golden wattle	5.2650	2.6325	0.2340	0.1170			3	Alves et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1a

olive	2.8272	1.4136	0.4774	0.2387			3	Alves et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1a
Portugese oak	4.8608	2.4304	0.3822	0.1911			3	Alves et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1a
holm oak	5.4468	2.7234	0.2244	0.1122			3	Alves et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1a
Quercus pyrenaica	9.0000	3.0000	0.5790	0.0890			2	Calvo et al. (2015)	traditional Portuguese brick open fireplace	1
Pinus nigra	10.5000	3.4000	0.7900	0.1900			2	Calvo et al. (2015)	traditional Portuguese brick open fireplace	1
Facus sylvativa	3.9000	0.9200	0.4300	0.2300			2	Calvo et al. (2015)	traditional Portuguese brick open fireplace	1
Quercus pyrenaica	9.1000	2.7000	0.9000	0.2000			6	Calvo et al. (2015)	a cast iron woodstove (Solzaima, model Sahara)	1
Pinus nigra	2.9000	1.1000	0.8790	0.0480			6	Calvo et al. (2015)	a cast iron woodstove (Solzaima, model Sahara)	1
Facus sylvativa	1.6000	0.5000	0.4300	0.1300			6	Calvo et al. (2015)	a cast iron woodstove (Solzaima, model Sahara)	1
tur (woody stalks)	1.6830		0.4080				1	Habib et al. (2008)	U-shaped, single-pot mud stove	1
cotton (woody stalks)	1.3440		0.6720				1	Habib et al. (2008)	U-shaped, single-pot mud stove	1
soyabean (woody stalks)	4.2680		0.7760				1	Habib et al. (2008)	U-shaped, single-pot mud stove	1
mustard (woody stalks)	4.7960		0.6540				1	Habib et al. (2008)	U-shaped, single-pot mud stove	1
cattle dung	2.3220		0.2160				1	Habib et al. (2008)	U-shaped, single-pot mud stove	2

jute (fibrous hollow stalks)	0.6290		0.3060				1	Habib et al. (2008)	U-shaped, single-pot mud stove	2
rice straw	4.6500		0.1860				1	Habib et al. (2008)	U-shaped, single-pot mud stove	2
jamun	1.5800	2.0300	0.4800	0.0850			2	Habib et al. (2008)	U-shaped, single-pot mud stove	1
neem	1.6500	1.9500	0.6100	0.0300			2	Habib et al. (2008)	U-shaped, single-pot mud stove	1
mango	1.6100	1.5700	0.6400	0.0640			2	Habib et al. (2008)	U-shaped, single-pot mud stove	1
Acacia	1.1000	0.5390	0.4500	0.1220			2	Habib et al. (2008)	U-shaped, single-pot mud stove	1
horsebean	1.2000	0.1700	1.2800	0.1000			2	Shen et al. (2010)	brick wok stove (rural)	2
peanut	1.0800		0.4930				1	Shen et al. (2010)	brick wok stove (rural)	2
soybean residue	1.1700	0.1800	1.3700	0.0400			2	Shen et al. (2010)	brick wok stove (rural)	2
cotton residue	0.3540	0.0410	1.3400	0.5800			2	Shen et al. (2010)	brick wok stove (rural)	2
rice	1.5000	0.1600	0.7490	0.4270			2	Shen et al. (2010)	brick wok stove (rural)	2
wheat	2.2700	1.3000	2.6400	1.0100			2	Shen et al. (2010)	brick wok stove (rural)	2
rape	1.7500	0.6300	2.3400	0.9200			2	Shen et al. (2010)	brick wok stove (rural)	2
sesame	2.3400	1.1200	1.0700	0.0300			2	Shen et al. (2010)	brick wok stove (rural)	2
corn	1.3600	0.2900	1.1100	0.0800			2	Shen et al. (2010)	brick wok stove (rural)	2
wheat stubble	1.3794	0.3012	0.4260	0.1147			3	Jimenez et al. (2007)	test burn chamber to mimic open burn conditions	3
wheat stubble	2.8120	1.6127	0.1660	0.1408			6	Jimenez et al. (2007)	open field	3
Kentucky Bluegrass	5.2248	2.2406	0.7650	0.3361			2	Jimenez et al. (2007)	open field	4
Kentucky Bluegrass	4.4637	1.2962	0.8155	0.4307			4	Jimenez et al. (2007)	test burn chamber to mimic open burn conditions	4

wheat straw	0.2900	0.1200	0.1600	0.0700				Sahai et al. (2007)	field burning	3
wheat straw	2.3800		1.5900				1	Sahai et al. (2007)	earlier lab experiments at NPL	3
wheat straw	1.2300		0.5200				1	Hays et al. (2005)	field open burn simulations	3
rice straw	8.9400		0.1700				1	Hays et al. (2005)	field open burn simulations	3
olive pits	0.9000	0.5700	0.1000	0.0600				AIRUSE LIFE (2016)	from pellet stove	2
maritime pine	2.5400	2.5100	0.6100	0.4300			3	Fernandes et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1
golden wattle	4.0700	2.6500	0.2900	0.1800			3	Fernandes et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1
eucalypt	5.1600	4.0300	0.3700	0.3000			3	Fernandes et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1
cork oak	4.8000	3.3800	0.4200	0.3300			3	Fernandes et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1
olive	4.5500	2.2200	0.4600	0.2400			3	Fernandes et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1
holm oak	3.0300	2.0500	0.2300	0.0900			3	Fernandes et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1
Portugese oak	6.1700	4.6200	0.3200	0.1500			3	Fernandes et al. (2011)	a cast iron woodstove (Solzaima, model Sahara)	1
maritime pine	2.9100	1.3000	0.6200	0.4900			3	Fernandes et al. (2011)	traditional Portuguese brick open fireplace	1
golden wattle	3.5300	3.1300	0.3400	0.2600			3	Fernandes et al. (2011)	traditional Portuguese brick open fireplace	1
eucalypt	5.1100	3.9000	0.3600	0.3600			3	Fernandes et al. (2011)	traditional Portuguese brick open fireplace	1

cork oak	10.0600	5.2400	0.6800	0.4000			3	Fernandes et al. (2011)	traditional Portuguese brick open fireplace	1
olive	9.1000	5.7400	0.3900	0.1600			3	Fernandes et al. (2011)	traditional Portuguese brick open fireplace	1
holm oak	7.2200	4.0300	0.3000	0.1100			3	Fernandes et al. (2011)	traditional Portuguese brick open fireplace	1
Portugese oak	6.0600	3.4000	0.3200	0.2000			3	Fernandes et al. (2011)	traditional Portuguese brick open fireplace	1
Chinese white poplar	0.6600	0.3200	0.8800	0.4900			3	Guofeng et al. (2012)	brick stove (rural)	1
elm	0.7900	0.1500	1.2000	0.3000			3	Guofeng et al. (2012)	brick stove (rural)	1
yellow locust	1.9000	1.5000	0.2100	0.1500			3	Guofeng et al. (2012)	brick stove (rural)	1
maple	0.1100	0.0100	0.0560	0.0040			3	Guofeng et al. (2012)	brick stove (rural)	1
fir	0.9700	0.8800	0.9500	0.2000			3	Guofeng et al. (2012)	brick stove (rural)	1
larch	0.1400	0.1100	0.3500	0.3400			3	Guofeng et al. (2012)	brick stove (rural)	1
water Chinese fir	0.3600	0.1700	0.8500	0.4500			3	Guofeng et al. (2012)	brick stove (rural)	1
cypress	0.8200	0.4500	0.7100	0.3900			3	Guofeng et al. (2012)	brick stove (rural)	1
oak	0.5400	0.6300	0.1300	0.1300			3	Guofeng et al. (2012)	brick stove (rural)	1
chinese pine	0.6000	0.3500	0.9400	0.4000			3	Guofeng et al. (2012)	brick stove (rural)	1

willow	0.2300	0.1000	0.4700	0.3000			3	Guofeng et al. (2012)	brick stove (rural)	1
Paulownia tomentosa	0.3900	0.1200	0.9400	0.5100			3	Guofeng et al. (2012)	brick stove (rural)	1
toon	0.1900	0.1300	0.5200	0.4100			3	Guofeng et al. (2012)	brick stove (rural)	1
white birch	0.6900	0.3200	0.6700	0.6100			3	Guofeng et al. (2012)	brick stove (rural)	1
Lespedeza	0.2100	0.1700	0.4800	0.4000			3	Guofeng et al. (2012)	brick stove (rural)	1
Buxus sinica	1.2000	0.1000	2.5000	1.7000			3	Guofeng et al. (2012)	brick stove (rural)	1
holly	0.7300	0.2800	1.6000	0.4000			3	Guofeng et al. (2012)	brick stove (rural)	1
bamboo	0.1300	0.0900	1.2000	0.5000			3	Guofeng et al. (2012)	brick stove (rural)	1
barley straw					0.0400	0.0000	2	Jenkins et al. (1996); a932-126b_1	wind tunnel	3
corn stover					0.2000	0.0141	2	Jenkins et al. (1996); a932-126b_1	wind tunnel	3
rice straw					0.5910	0.2150	8	Jenkins et al. (1996); a932-126b_1	wind tunnel	3
wheat straw					0.4700	0.2758	2	Jenkins et al. (1996); a932-126b_1	wind tunnel	3

seasoned oak					0.1671		1	DeAngelis et al. (1980)	nonbaffled stove	1
seasoned pine					0.2531		1	DeAngelis et al. (1980)	nonbaffled stove	1
Kentucky Blue-grass	15.0000	5.2000	0.5000	0.1100			4	Holder et al. (2017)	field measurements, Aerostat	4
Kentucky Blue-grass	11.0000	6.1000	0.3200	0.1000			4	Holder et al. (2017)	field measurements, ground	4
Kentucky Blue-grass			0.7600	0.3300			4	Holder et al. (2017)	field measurements, Aerostat, eBC	4
Kentucky Blue-grass			0.9300	0.0730			4	Holder et al. (2017)	field measurements, ground, eBC	4
wheat	9.4000	1.6000	0.5000	0.2000			4	Holder et al. (2017)	field measurements, Aerostat	3
wheat	11.2000	2.5000	0.2000	0.0000			4	Holder et al. (2017)	field measurements, ground	3
wheat			0.6000	0.1000			4	Holder et al. (2017)	field measurements, Aerostat, eBC	3
wheat			0.5000	0.1000			4	Holder et al. (2017)	field measurements, ground, eBC	3
wheat			0.7000	0.0900			8	Zhang et al. (2015)	field measurements, EF based on CO_2	3
rice			0.5600	0.0400			4	Zhang et al. (2015)	field measurements, EF based on CO_2	3
rapeseed			2.8900	0.7000			4	Zhang et al. (2015)	field measurements, EF based on CO_2	3
wheat			0.4300	0.1000			8	Zhang et al. (2015)	field measurements, EF based on CO	3

rice			0.2500	0.1100			4	Zhang et al. (2015)	field measurements, EF based on CO	3
rapeseed			1.0100	0.2700			4	Zhang et al. (2015)	field measurements, EF based on CO	3
charcoal burning	1.7800	2.8000	0.6500	0.3000			8	Keita et al. (2018)	trad. stoves (metal or baked earth), field meas.; per kg charcoal	5
charcoal making	3.9300	1.0100	0.2200	0.1600			8	Keita et al. (2018)	trad. stoves (metal or baked earth), field meas.; per kg wood	6
wood (iroko)	6.5000	1.9800	0.5200	0.3900			4	Keita et al. (2018)	traditional charcoal-making furnaces, field meas.	1
wood(hevea)	15.6100	6.4400	1.4500	0.6100			4	Keita et al. (2018)	traditional charcoal-making furnaces, field meas.	1
charcoal making					0.1860	0.1350	7	Park et al. (2013)	charcoal kiln, field meas.; per kg wood	6
wheat stubble	1.9000	1.0482					6	Dhammapala et al. (2007a)	test burn facility	3
Kentucky Bluegrass stubble	6.9000	2.2346					29	Dhammapala et al. (2007a)	test burn facility	4
wheat stubble			0.3500	0.2382			11	Dhammapala et al. (2007a)	test burn facility	3
Kentucky Bluegrass stubble			0.6300	0.1472			29	Dhammapala et al. (2007a)	test burn facility	4
wheat stubble	2.7360	1.0080					4	Dhammapala et al. (2007b)	field burning	3
Kentucky Bluegrass stubble	6.9330						1	Dhammapala et al. (2007b)	field burning	4

wheat stubble			0.3760	0.2890			6	Dhammapala et al. (2007b)	field burning	3
Kentucky Blue-grass stubble			0.7980	0.3440			2	Dhammapala et al. (2007b)	field burning	4
grass, ground	7.0000		0.6200				1	Strand et al. (2016)	ground	4
grass, aerostat	6.5000		0.5600				1	Strand et al. (2016)	Aerostat	4
grass, ground			1.1000				1	Strand et al. (2016)	ground; continuous eBC	4
grass, aerostat			0.9100				1	Strand et al. (2016)	Aerostat; continuous eBC	4
grass (Brazil)	5.1000	2.2500	0.6500	0.4500	0.4400	0.1800	6	Ferek et al. (1998)	airborne measurements	4
fuel wood, Delhi	0.8500	0.7000	0.3700	0.1800			101	Saud et al. (2012)	dilution sampler	1
fuel wood, Punjab	0.9300	0.9600	0.4400	0.2900			139	Saud et al. (2012)	dilution sampler	1
fuel wood, Haryana	0.7800	0.4100	0.4200	0.0700			92	Saud et al. (2012)	dilution sampler	1
fuel wood, Uttar Pradesh	1.3200	1.0000	0.3100	0.1200			149	Saud et al. (2012)	dilution sampler	1
fuel wood, Uttarakhand	0.9200	0.5400	0.2700	0.0800			181	Saud et al. (2012)	dilution sampler	1
fuel wood, Bihar	1.2800	0.9900	0.3600	0.1900			85	Saud et al. (2012)	dilution sampler	1
fuel wood, West Bengal	0.5500	0.7000	0.2500	0.1300			19	Saud et al. (2012)	dilution sampler	1
crop residue, Delhi	2.1000	1.4400	0.5700	0.3600			20	Saud et al. (2012)	dilution sampler	2
crop residue, Punjab	0.5600	0.2800	0.2500	0.0700			40	Saud et al. (2012)	dilution sampler	2

crop residue, Haryana	0.9400	0.7100	0.4200	0.1300			35	Saud et al. (2012)	dilution sampler	2
crop residue, Uttar Pradesh	2.3400	1.2800	0.3900	0.1900			107	Saud et al. (2012)	dilution sampler	2
crop residue, Bihar	1.8700	1.6600	0.4300	0.5200			105	Saud et al. (2012)	dilution sampler	2
crop residue, West Bengal	0.9700	0.8800	0.1800	0.1100			20	Saud et al. (2012)	dilution sampler	2
dung cake, Delhi	4.5100	1.3400	0.9000	0.3500			95	Saud et al. (2012)	dilution sampler	2
dung cake, Punjab	4.6400	0.7800	0.5900	0.2400			48	Saud et al. (2012)	dilution sampler	2
dung cake, Haryana	3.7800	0.4700	0.5400	0.3400			38	Saud et al. (2012)	dilution sampler	2
dung cake, Uttar Pradesh	4.4100	1.1900	0.4100	0.2100			45	Saud et al. (2012)	dilution sampler	2
dung cake, Bihar	4.1400	1.4800	0.2800	0.2100			68	Saud et al. (2012)	dilution sampler	2
dung cake, West Bengal	1.7400	1.1000	0.2200	0.1300			8	Saud et al. (2012)	dilution sampler	2
rice straw	2.7838	1.1874	0.4789	0.2891			4	Oanh et al. (2011)	field burning	3
wheat straw	2.6000	1.8000	0.4600	0.1900			3	Wei et al. (2014)	improved two-pot stove with chimney, 1-year old	2
rape straw	0.5800	0.1700	0.4700	0.4800			3	Wei et al. (2014)	improved two-pot stove with chimney, 1-year old	2
rice straw	1.1000	0.9000	0.5100	0.3700			3	Wei et al. (2014)	improved two-pot stove with chimney, 1-year old	2
cotton straw	3.1000	4.5000	1.2000	1.4000			3	Wei et al. (2014)	improved two-pot stove with chimney, 1-year old	2
wheat straw	4.1000	1.8000	1.4000	0.9000			3	Wei et al. (2014)	improved two-pot stove with chimney, 15-year old	2

rape straw	4.9000	6.5000	2.7000	2.4000			3	Wei et al. (2014)	improved two-pot stove with chimney, 15-year old	2
rice straw	1.5000	0.6000	0.6400	0.1900			3	Wei et al. (2014)	improved two-pot stove with chimney, 15-year old	2
cotton straw	2.5000	1.8000	0.9600	0.9000			3	Wei et al. (2014)	improved two-pot stove with chimney, 15-year old	2
wheat straw	4.0659	0.3297	0.3187	0.0220			3	Tian et al. (2017)	traditional stove	2
maize straw	7.0330	1.9780	0.5275	0.0769			3	Tian et al. (2017)	traditional stove	2
rice straw	8.4615	1.4286	0.5714	0.0659			3	Tian et al. (2017)	traditional stove	2
charcoal burning					0.5000	0.3000	1	Gadi et al. (2011)	U-shaped chimney	5

References

AIRUSE LIFE (2016). *Emission factors for biomass burning, Report 9.* Tech. rep. AIRUSE LIFE 11 ENV/ES/584.

Alves, C., C. Gonçalves, A. P. Fernandes, L. Tarelho, and C. Pio (2011). "Fireplace and woodstove fine particle emissions from combustion of western Mediterranean wood types". In: *Atmos. Res.* 101.3. International Conference on Nucleation and Atmospheric Aerosols (Part 2), pp. 692–700. ISSN: 0169-8095. DOI: https://doi.org/10.1016/j.atmosres.2011.04.015. URL: http://www.sciencedirect.com/science/article/pii/S0169809511001268.

Bond, T. C., D. G. Streets, K. F. Yarber, S. M. Nelson, J.-H. Woo, and Z. Klimont (2004). "A technology-based global inventory of black and organic carbon emissions from combustion". In: *J. Geophys. Res.-Atmos.* 109.D14. DOI: 10.1029/2003JD003697. eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2003JD003697. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2003JD003697.

Calvo, A., V. Martins, T. Nunes, M. Duarte, R. Hillamo, K. Teinilä, V. Pont, A. Castro, R. Fraile, L. Tarelho, and C. Alves (2015). "Residential wood combustion in two domestic devices: Relationship of different parameters throughout the combustion cycle". In: *Atmos. Environ.* 116, pp. 72–82. ISSN: 1352-2310. DOI: https://doi.org/10.1016/j.atmosenv.2015.06.012. URL: http://www.sciencedirect.com/science/article/pii/S1352231015301552.

Cao, G., X. Zhang, S. Gong, and F. Zheng (2008). "Investigation on emission factors of particulate matter and gaseous pollutants from crop residue burning". In: *J. Environ. Sci.* 20, pp. 50–55.

DeAngelis, D. G., D. S. Ruffin, and R. B. Reznik (1980). *Preliminary Characterization of Emissions from Wood-fired Residential Combustion Equipment.* U.S. Environmental Protection Agency, EPA-600/7-80-040.

Dhammapala, R., C. Claiborn, J. Jimenez, J. Corkill, B. Gullett, C. Simpson, and M. Paulsen (2007a). "Emission factors of PAHs, methoxyphenols, levoglucosan, elemental carbon and organic carbon from simulated wheat and Kentucky bluegrass stubble burns". In: *Atmos. Environ.* 41, pp. 2660–2669.

Dhammapala, R., C. Claiborn, C. Simpson, and J. Jimenez (2007b). "Emission factors from wheat and Kentucky bluegrass stubble burning: Comparison of field and simulated burn experiments". In: *Atmos. Environ.* 41, pp. 1512–1520.

Ferek, R. J., J. S. Reid, P. V. Hobbs, D. R. Blake, and C. Liousse (1998). "Emission factors of hydrocarbons, halocarbons, trace gases and particles from biomass burning in Brazil". In: *J. Geophys. Res.* 103.D24, pp. 32107–32118.

Fernandes, A. P., C. Alves, C. Gonçalves, L. Tarelho, C. Pio, C. Schimdl, and H. Bauer (2011). "Emission factors from residential combustion appliances burning Portuguese biomass fuels". In: *J. Environ. Monit.* 11, pp. 3196–3206. DOI: 10.1039/c1em10500k.

Gadi, R., U. C. Kulshrestha, A. K. Sarkar, S. C. Garg, and D. C. Parashar (2011). "Emissions of SO_2 and NO_x from biofuels in India". In: *Tellus B: Chemical and Physical Meteorology* 55.5, pp. 787–795. DOI: 10.3402/tellusb.v55i3.16370.

Goodchild, H. (2007). "Modelling Roman agricultural production in the middle Tiber Valley, Central Italy". PhD thesis. Institute of Archaeology and Antiquity, School of Historical Studies, The University of Birmingham.

Guofeng, S., W. Siye, W. Wen, Z. Yanyan, M. Yujia, W. Bin, W. Rong, L. Wei, S. Huizhong, H. Ye, Y. Yifeng, W. Wei, W. Xilong, W. Xuejun, and T. Shu (Apr. 2012). "Emission Factors, Size Distributions, and Emission Inventories of Carbonaceous Particulate Matter from Residential Wood Combustion in Rural China”. In: *Environ. Sci. Technol.* 46.7, pp. 4207–4214. ISSN: 0013-936X. DOI: 10.1021/es203957u. URL: https://doi.org/10.1021/es203957u.

Habib, G., C. Venkataraman, T. C. Bond, and J. J. Schauer (2008). “Chemical, Microphysical and Optical Properties of Primary Particles from the Combustion of Biomass Fuels”. In: *Environ. Sci. Technol.* 42, pp. 8829–8834.

Hamilton, D., S. Hantson, C. Scott, J. Kaplan, K. Pringle, L. Nieradzik, A. Rap, G. Folberth, D. Spracklen, and K. Carslaw (Dec. 2018). “Reassessment of pre-industrial fire emissions strongly affects anthropogenic aerosol forcing”. English. In: *Nat. Commun.* 9.1. ISSN: 2041-1723. DOI: 10.1038/s41467-018-05592-9.

Harris, W. (2013). “Defining and Detecting Mediterranean Deforestation, 800BCE to 700CE”. In: *The Ancient Mediterranean Environment between Science and History*. Leiden, The Netherlands: Brill, pp. 173–194. ISBN: 9789004254053. URL: https://brill.com/view/book/edcoll/9789004254053/B9789004254053_008.xml.

Hays, M. D., P. M. Fine, C. D. Geron, M. J. Kleeman, and B. K. Gullett (2005). “Open burning of agricultural biomass: Physical and chemical properties of particle-phase emissions”. In: *Atmos. Environ.* 39, pp. 6747–6764.

Holder, A., B. Gullett, S. Urbanski, R. Elleman, S. O’Neill, D. Tabor, W. Mitchell, and K. Baker (2017). “Emissions from prescribed burning of agricultural fields in the Pacific Northwest”. In: *Atmos. Environ.* 166, pp. 22–33. ISSN: 1352-2310. DOI: https://doi.org/10.1016/j.atmosenv.2017.06.043. URL: http://www.sciencedirect.com/science/article/pii/S1352231017304247.

Hopkins, K. (2017). “Models, Ships and Staples”. In: *Sociological Studies in Roman History*. Ed. by C. Kelly. Cambridge Classical Studies. Cambridge University Press, pp. 213–268. DOI: 10.1017/CBO9781139093552.009.

Jenkins, B. M., S. Q. Turn, R. B. Williams, M. Goronea, H. Abd-el-Fattah, J. Mehlschau, N. Raubach, D. P. Y. Chang, M. Kang, S. V. Teague, O. G. Raabe, D. E. Campbell, T. A. Cahill, L. Pritchett, J. Chow, and A. D. Jones (1996). *Atmospheric Pollutant Emission Factors From Open Burning of Agricultural and Forest Biomass by Wind Tunnel Simulations: Volume 1-3*. Research rep. California Environmental Protection Agency, contract NO. A932-126.

Jimenez, J. R., C. S. Claiborn, R. S. Dhammapala, and C. D. Simpson (2007). “Methoxyphenols and Levoglucosan Ratios in PM2.5 from Wheat and Kentucky Bluegrass Stubble Burning in Eastern Washington and Northern Idaho”. In: *Environ. Sci. Technol.* 41, pp. 7824–7829.

Keita, S., C. Liousse, V. Yoboué, P. Dominutti, B. Guinot, E.-M. Assamoi, A. Borbon, S. L. Haslett, L. Bouvier, A. Colomb, H. Coe, A. Akpo, J. Adon, J. Bahino, M. Doumbia, J. Djossou, C. Galy-Lacaux, E. Gardrat, S. Gnamien, J. F. Léon, M. Ossohou, E. T. N’Datchoh, and L. Roblou (2018). “Particle and VOC emission factor measurements for anthropogenic sources in West Africa”. In: *Atmos. Chem. Phys.* 18.10, pp. 7691–7708. DOI: 10.5194/acp-18-7691-2018. URL: https://www.atmos-chem-phys.net/18/7691/2018/.

Li, C., Y. Hu, F. Zhang, J. Chen, Z. Ma, X. Ye, X. Yang, L. Wang, X. Tang, R. Zhang, M. Mu, G. Wang, H. Kan, X. Wang, and A. Mellouki. (2017). “Multi-pollutant emissions from the burning of major agricultural residues in China and the related health-economic effects”. In: *Atmos. Chem. Phys.* 17, pp. 4957–4988.

Lohri, C. R., H. M. Rajabu, D. J. Sweeney, and C. Zurbrügg (2016). “Char fuel production in developing countries – A review of urban biowaste carbonization”. In: *Renewable Sustainable Energy Rev.* 59, pp. 1514–1530. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2016.01.088. URL: http://www.sciencedirect.com/science/article/pii/S1364032116001180.

McDonald, J. D., B. Zielinska, E. M. Fujita, J. C. Sagebiel, J. C. Chow, and J. G. Watson (2000). "Fine Particle and Gaseous Emission Rates from Residential Wood Combustion". In: *Environ. Sci. Technol.* 34.11, pp. 2080–2091. DOI: 10.1021/es9909632. eprint: https://doi.org/10.1021/es9909632. URL: https://doi.org/10.1021/es9909632.

Mietz, M. (2016). "The fuel economy of public bathhouses in the Roman Empire". MA thesis. Faculty of Arts and Philosophy, Campus Boekentoren, Blandijnberg 2, B-9000 Ghent, Belgium: Ghent University.

Oanh, N. T. K., B. T. Ly, D. Tipayarom, B. R. Manandhar, P. Prapat, C. D. Simpson, and L.-J. S. Liu (2011). "Characterization of particulate matter emission from open burning of rice straw". In: *Atmos. Environ.* 45, pp. 493–502.

Olson, S. D. (1991). "Firewood and charcoal in Classical Athens". In: *Hesperia: The Journal of the American of Classical Studies at Athens* 60.3, pp. 411–420.

Pandey, A., S. Patel, S. Pervez, S. Tiwari, G. Yadama, J. C. Chow, J. G. Watson, P. Biswas, and R. K. Chakrabarty (2017). "Aerosol emissions factors from traditional biomass cookstoves in India: insights from field measurements". In: *Atmos. Chem. Phys.* 17, pp. 13721–13729.

Park, S.-K., S.-J. Choi, J.-Y. Kim, G.-J. Park, U.-H. Hwang, J.-J. Lee, and T.-S. Kim (2013). "A Field Survey on the Characteristics of Air Pollutants Emission from Commercial Charcoal Kiln". In: *J. Kosae* 29.5, pp. 601–614.

Rowan, E. (2015). "Olive oil pressing waste as a fuel source in Antiquity". In: *Am. J. Archaeol.* 119.4, pp. 465–482. DOI: 10.3764/aja.119.4.0465.

Sahai, S., C. Sharma, D. P. Singh, C. K. Dixit, N. Singh, P. Sharma, K. Singh, S. Bhatt, S. Ghude, V. Gupta, R. K. Gupta, M. K. Tiwari, S. C. Garg, A. P. Mitra, and P. K. Gupta (2007). "A study for development of emission factors for trace gases and carbonaceous particulate species from in situ burning of wheat straw in agricultural fields in india". In: *Atmos. Environ.* 41, pp. 9173–9186.

Saud, T., R. Gautam, T. K. Mandal, S. Gadi R., S. D. P., S. K., M. Dahiya, and M. Saxena (2012). "Emission estimates of organic and elemental carbon from household biomass fuel used over the Indo-Gangetic Plain (IGP), India". In: *Atmos. Environ.* 61, pp. 212–220.

Shen, G., Y. Yang, W. Wang, S. Tao, C. Zhu, Y. Min, M. Xue, J. Ding, B. Wang, R. Wang, H. Shen, W. Li, X. Wang, and A. G. Russell (Sept. 2010). "Emission Factors of Particulate Matter and Elemental Carbon for Crop Residues and Coals Burned in Typical Household Stoves in China". In: *Environ. Sci. Technol.* 44.18, pp. 7157–7162. ISSN: 0013-936X. DOI: 10.1021/es101313y. URL: https://doi.org/10.1021/es101313y.

Sinclair, T. R. (1998). "Historical Changes in Harvest Index and Crop Nitrogen Accumulation. Review and Interpretation". In: *Crop Sci.* 38.3.

Smith, K. R. (2000). *Greenhouse gases from small-scale combustion devices in developing countries Phase IIa. Household Stoves in India.* Tech. rep. U.S. Environmental Protection Agency.

Spurr, M. S. (1986). *Arable cultivation in Roman Italy. c.200 B.C.-c.A.D. 100.* 31-34 Gordon Square, London WC1H 0PP: The Society for the Promotion of Roman Studies.

Strand, T., B. Gullett, S. Urbanski, S. O'Neill, B. Potter, J. Aurell, A. Holder, N. Larkin, M. Moore, and M. Rorig (2016). "Grassland and forest understorey biomass emissions from prescribed fires in the southeastern United States – RxCADRE 2012". In: *Int. J. Wildland Fire* 25, pp. 102–113.

Tataryn (2016). *The Roman Empire and its clients in 117 AD during the reign of emperor Trajan.* Ed. by Wikimedia Commons, retrieved 14 Nov 2018. URL: https://commons.wikimedia.org/wiki/File:Roman_Empire_Trajan_117AD.png.

Temin, P. (2006). "The Economy of the Early Roman Empire". In: *J. Econ. Perspect.* 20.1, pp. 133–151.

Tian, J., H. Ni, J. Cao, Y. Han, Q. Wang, X. Wang, L.-W. Chen, J. C. Chow, J. G. Watson, C. Wei, J. Sun, T. Zhang, and R. Huang (2017). "Characteristics of carbonaceous particles from residential coal combustion and agricultural biomass burning in China". In: *Atmos. Pollut. Res.* 8.3, pp. 521–527. ISSN: 1309-1042. DOI: https://doi.org/10.1016/j.apr.2016.12.006. URL: http://www.sciencedirect.com/science/article/pii/S1309104216302896.

Turn, S. Q., B. M. Jenkins, J. C. Chow, L. C. Pritchett, D. Campbell, T. Cahill, and S. A. Whalen (1997). "Elemental characterizationof particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels". In: *J. Geophys. Res.* 102.D3, pp. 3683–3699.

Van Marle, M. J. E., S. Kloster, B. I. Magi, J. R. Marlon, A.-L. Daniau, R. D. Field, A. Arneth, M. Forrest, S. Hantson, N. M. Kehrwald, W. Knorr, G. Lasslop, F. Li, S. Mangeon, C. Yue, J. W. Kaiser, and G. R. van der Werf (2017). "Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750–2015)". In: *Geosci. Model Dev.* 10.9, pp. 3329–3357. DOI: 10.5194/gmd-10-3329-2017. URL: https://www.geosci-model-dev.net/10/3329/2017/.

Veal, R. (2017). "Wood and Charcoal for Rome: Towards an Understanding of Ancient Regional Fuel Economics". In: *The Economic Integration of Roman Italy.* Leiden, The Netherlands: Brill, pp. 388–406. ISBN: 9789004345027. URL: https://brill.com/view/book/edcoll/9789004345027/B9789004345027_017.xml.

Wei, S., G. Shen, Y. Zhang, M. Xue, H. Xie, P. Lin, Y. Chen, X. Wang, and S. Tao (2014). "Field measurement on the emissions of PM, OC, EC and PAHs from indoor crop straw burning in rural China". In: *Environ. Pollut.* 184, pp. 18–24. ISSN: 0269-7491. DOI: https://doi.org/10.1016/j.envpol.2013.07.036. URL: http://www.sciencedirect.com/science/article/pii/S0269749113004120.

Wood, T. S. and S. Baldwin (1985). "Fuelwood and charcoal use in developing countries". In: *Ann. Rev. Energy* 10, pp. 407–429.

Yevich, R. and J. A. Logan (2003). "An assessment of biofuel use and burning of agricultural waste in the developing world". In: *Global Biogeochem. Cycles* 17.4. DOI: 10.1029/2002GB001952.

Zhang, J., K. Smith, Y. Ma, S. Ye, F. Jiang, W. Qi, P. Liu, M. Khalil, R. Rasmussen, and S. Thorneloe (2000). "Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors". In: *Atmos. Environ.* 34.26, pp. 4537–4549. ISSN: 1352-2310. DOI: https://doi.org/10.1016/S1352-2310(99)00450-1. URL: http://www.sciencedirect.com/science/article/pii/S1352231099004501.

Zhang, T., M. J. Wooster, D. C. Green, and B. Main (2015). "New field-based agricultural biomass burning trace gas, PM2.5, and black carbon emission ratios and factors measured in situ at crop residue fires in Eastern China". In: *Atmos. Environ.* 121. Interdisciplinary Research Aspects of Open Biomass Burning and its Impact on the Atmosphere, pp. 22–34. ISSN: 1352-2310. DOI: https://doi.org/10.1016/j.atmosenv.2015.05.010. URL: http://www.sciencedirect.com/science/article/pii/S1352231015300807.