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Global combustion: the connection between fossil fuel and biomass burning emissions (1997–2010)

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Humans use combustion for heating and cooking, managing lands, and, more recently, for fuelling the industrial economy. As a shift to fossil-fuel-based energy occurs, we expect that anthropogenic biomass burning in open landscapes will decline as it becomes less fundamental to energy acquisition and livelihoods. Using global data on both fossil fuel and biomass burning emissions, we tested this relationship over a 14 year period (1997–2010). The global average annual carbon emissions from biomass burning during this time were 2.2 Pg C per year (±0.3 s.d.), approximately one-third of fossil fuel emissions over the same period (7.3 Pg C, ±0.8 s.d.). There was a significant inverse relationship between average annual fossil fuel and biomass burning emissions. Fossil fuel emissions explained 8% of the variation in biomass burning emissions at a global scale, but this varied substantially by land cover. For example, fossil fuel burning explained 31% of the variation in biomass burning in woody savannas, but was a non-significant predictor for evergreen needleleaf forests. In the land covers most dominated by human use, croplands and urban areas, fossil fuel emissions were more than 30- and 500-fold greater than biomass burning emissions. This relationship suggests that combustion practices may be shifting from open landscape burning to contained combustion for industrial purposes, and highlights the need to take into account how humans appropriate combustion in global modelling of contemporary fire. Industrialized combustion is not only an important driver of atmospheric change, but also an important driver of landscape change through companion declines in human-started fires.

This article is part of the themed issue 'The interaction of fire and mankind'.

1. Introduction

Humans have used fire for their own benefit for millennia [1–3], yet it is difficult to disentangle the human and natural component of global fire regimes. Humans can alter fire regimes in three ways: changing ignition density and distribution, altering available fuels, and shifting seasonality of burning [4]. A fourth and the most recent driver, anthropogenic climate change, can alter both the window of conducive fire weather and fuel characteristics [5–7]. It is estimated that only a quarter of the world's land surface exhibits fire regimes unaltered by people, primarily in swaths of northern latitude evergreen forests [8]. One clear expression of the effect of human agency on fire regimes is the application of fire for contemporary agricultural purposes [9], which accounted for 8–11% of global fire activity from 2001 to 2003 [10]. Current global fire data products from satellites and inventories offer us a unique perspective on our fire planet [11], and enable exploration of the natural and human drivers underlying the diversity and distribution of fire on the Earth. Yet, it is difficult to separate these two drivers. We argue that quantification of the direct and indirect human imprint on fire in the modern era can be aided by comparing fossil fuel and biomass burning, two forms of combustion. Here, we define biomass burning as deforestation, grassland, savanna, forest, agricultural and peat fires as detected at the Earth surface by the moderate resolution imaging spectroradiometer (MODIS) (*sensu* [12]). This does not include burning of biomass for domestic purposes in hearths and combustion chambers, such as fuelwood used in cooking stoves nor industrial biofuel derived from crops.

We posit here that fossil fuel combustion and biomass burning are linked, that as a shift to consumption of fossil-fuel-based energy occurs, there is less of a need to rely on biomass burning as fundamental to energy acquisition and livelihoods. This ‘pyric transition’, as first identified and named by Pyne, is defined by the shift in human practices from burning landscapes as fundamental to their livelihoods to burning fossil fuels [4,13,14]. The major hypothesis that follows is that with industrialized burning of fossil fuels there is a marked reduction of human-started fire in the landscape, because these fires are replaced by other technologies, actively suppressed, prescribed only for nature preserves, or no longer set.

(a) Anthropogenic predictors of global fire patterns

Human population density [15–17], economic development metrics [17,18] and the overall human footprint [19] have been linked to global fire patterns. For example, a modern-era study shows that population density relates strongly to burned area for more than half the global land area, and has a hump-shaped relationship [15]. One potential explanation is that as population density increases fire activity increases owing to access and use of the landscape; fires then decline as the incentive to suppress fires increases with greater risk to infrastructure associated with permanent and higher density settlements. This hump-shaped relationship has been demonstrated at local scales over the past couple of hundred years in Missouri [20] and over the past few decades in California [21]. In some studies, ignitions from people have been assumed to peak at around 10 people km^{-2} [22,23], which has been used to extrapolate the effect on fire activity over the last millennium [16]. At a global scale, fire frequency exponentially declines after density reaches one person km^{-2} [24]. Lower population density has been shown to be associated with higher interannual variability in active fire detections and shorter fire season duration [17]. In addition, fires tend to be smaller in agricultural regions across the globe [25], where population densities may also be low. Other studies have looked at development predictors of fire activity, such as gross domestic product (GDP), which is associated with lower active fire detections [17] and burned area [18]. The underlying mechanism explaining the reduction in fire activity with high population density and high GDP should therefore relate to a fundamental shift in the reliance on combustion of biomass in open landscapes to fossil fuel burning for livelihoods.

(b) Fossil fuel and biomass burning often considered separately

The contribution of biomass and fossil fuel combustion to greenhouse gases in the atmosphere has been discussed separately in the literature [12,26–29]. From 2000 to 2009, fossil fuel emissions increased 3.2% yr^{-1} on average [29], whereas biomass burning emissions showed high interannual variability across a similar time period, from 1997 to 2009 [12]. The direct relationship between fossil fuel combustion and biomass burning has not been explored with global data from recent decades, although this link has been identified from a historical perspective, where the geography of combustion of living biomass has been contrasted with the geography of fossil fuel burning [13]. There is a marked difference between hunter–gatherer fire, agricultural fire and industrial fire, with a tendency for sequential replacement [4,13]. The ‘pyric transition’ is thus fundamental to understanding the connection between fossil fuel burning and the anthropogenic promotion and suppression of biomass burning in open landscapes.

We suggest that there is a link between fossil fuel and biomass burning that derives from peoples’ shifting use of combustion. Here, we test this hypothesis by using global data on emissions from landscape burning from the Global Fire Emissions Database 4 (GFED4) and from fossil fuel burning from the Carbon Dioxide Information Analysis Center (CDIAC). We expect that this relationship varies based on underlying fuel characteristics, and therefore, incorporate land cover from MODIS. Overall, we test the prediction that with industrialized burning there is a loss of fire in the landscape and consequent emissions.

2. Methods

(a) Data sources and processing

This study uses three global-extent, publically available data sources: fossil fuel carbon emissions from the CDIAC (http://cdiac.ornl.gov), biomass burning carbon emissions from the GFED4s (globalfiredata.org) and MODIS land cover (http://glcf.umd.edu/data/lc/). The GFED4s product provides monthly carbon emissions (0.25 degree resolution) from biomass burning by integrating the Carnegie–Ames–Stanford–Approach biogeochemical model with satellite-derived estimates of area burned, fire activity, and plant productivity. GFED4s is based on an updated version of van der Werf *et al.* [12] with MODIS-burned area [30] and boosted by small fire-burned area [27]. It is important to note that the GFED4s product includes emissions from open landscape burning, and not emissions from the burning of biomass to fuel power plants. The CDIAC data are annual emissions (1.0 degree resolution) derived from national mass-emissions data of fossil fuel combustion. Within-country estimates are related to population density [31]. We disaggregated the CDIAC data to match the spatial resolution of the GFED4s data. We used a 0.5 degree resolution global mosaic of 2010 MODIS land cover data [32,33] to analyse emissions by land cover type. We resampled the MODIS data to match the resolution of CDIAC and GFED4s data. Summary statistics, including mean (Tg C yr^{-1}), standard deviation (Tg C yr^{-1}), and coefficient of variation (%) for emissions from biomass burning and fossil fuels, were calculated globally and by land cover type. In addition, the ratio of annual mean emissions from fossil fuel and biomass burning was calculated by land cover type.

The human influence on landscape biomass burning is difficult to disentangle within global datasets. We assume that a substantial, but unknown portion, of biomass burning is the result of human-started fires and therefore use the full spatial and temporal extent of the GFED4s dataset. Evidence to support this assumption comes from many parts of the world. Over the past decade in the USA, over 80% of all fires fought by government agencies were started by people [34]. In the Amazon, present-day fire activity is linked to deforestation fires and pasture maintenance [35]. In Indonesia, extreme fire seasons are linked to severe drought, but can be amplified by human land use [36,37]. At a global scale, a mismatch in the fire season from the ideal climate window to burn demonstrates how people may be altering fire seasonality across all major biomes [38]. In southern Africa, it is notable how lightning strike seasonality and the seasonality of fires do not co-align, pointing towards human influence on ignition density and temporal distribution [39].

(b) Geospatial analysis

To relate biomass and fossil fuel burning, we developed a global map demonstrating how the two variables relate spatially. We scaled average global emissions from 1997 to 2010 by grid cell from zero to one by dividing each cell's emissions by the maximum emissions across all cells. We re-classified the cells according to four categories of emissions: zero, low, medium and high for biomass burning and fossil fuels. We designated classes as follows: the zero class corresponds to a scaled value of zero, low are values between zero and the first quantile of scaled data (after zeros were removed), medium are values between the first and third quantile, and high are values between the third quantile and one. We then mapped all 16 possible combinations of biomass burning (bb) by fossil fuel (ff) burning classes, and calculated the total area in each category. To simplify visual interpretation, we combined several categories as described below. We highlighted the areas of greatest contrast, namely where biomass burning was low but fossil fuel emissions were high (bb low/ff high), and where fossil fuel emissions were low but biomass burning was high (bb high/ff low). We also highlight where emissions from both were high (bb high/ff high).

(c) Linear regression

Linear regression was used to model biomass burning emissions as a function of fossil fuel emissions, globally and by land cover type. Biomass burning was treated as the dependent variable and fossil fuel burning as the independent variable. To maintain independence of grid cells (i.e. to reduce spatial autocorrelation in the data), the regression modelling was only performed on a random subset of 30% of the data. Further, as substantial portions of the land surface did not exhibit either fossil fuel or biomass burning during the study period, the analysis was constrained to the portion that had emissions greater than zero for both variables. Water, and snow and ice were cover types that were excluded from the analysis. Both variables were log-transformed prior to analysis, and were normally distributed. All statistical analysis was conducted with the R software package [40].

3. Results

(a) Average annual biomass and fossil fuel burning emissions

From 1997 to 2010, global average annual fossil fuel emissions were 7.3 Pg C (±0.8 s.d.) per year, whereas biomass burning emissions were 2.2 Pg C per year (±0.3 s.d.)—approximately one-third of fossil fuel emissions. Fossil fuel emissions show an increasing trend over time, whereas biomass burning does not; climate variables have been shown to be a strong driver of the interannual variation in biomass burning [13]. Human-dominated landscapes, urban areas and croplands, released 0.0003 Pg C per year (±0.0002 s.d.) and 0.0599 Pg C per year (±0.0074 s.d.) in biomass burning emissions, whereas they released 0.1 Pg C per year (±0.0038 s.d.) and 2.0 Pg C per year (±0.3 s.d.) of fossil fuel emissions (table 1); or in other words, the emissions from fossil fuel burning were more than 500-fold and 30-fold higher than those from biomass burning in urban and cropland areas, respectively.

(b) Global pattern of combustion emissions

The geography of combustion is notable in that areas with high biomass burning are not concurrent with areas that have high emissions from fossil fuel burning (figure 1). The total area that had any biomass burning was 63% of the global land surface (at 0.25 degree resolution), whereas 81% of the global land surface exhibits fossil fuel burning (at 1 degree resolution; figure 1). The spatial overlap between areas that have both high fossil fuel and biomass burning emissions was low, only 2.2 million km^2, about 1.5% of the Earth's land surface (table 2 and figure 2). The extent of areas with high biomass burning and low fossil fuel emissions was 10.3 million km^2, while the reverse, areas with high fossil fuel burning and low biomass burning covered 4.9 million km^2 (figure 2). Most of the overlap between biomass and fossil fuel burning is captured by areas that have a moderate amount of both, 17.2 million km^2. There is also a strong latitudinal pattern: fossil fuel emissions dominate in the northern latitudes, whereas biomass burning emissions dominate in the middle to southern latitudes (figure 3).

(c) Fossil fuel emissions as a predictor of biomass burning emissions

The overall trend is for biomass burning emissions to be lower where fossil fuel emissions are higher (figure 4). On a global scale, fossil fuel burning emissions explain 8% of the variation in biomass burning emissions (table 3; $F_{1,34657} = 2956$, p-value < 0.0001, with an adjusted R-squared $= 0.079$). Average biomass burning emissions decreased by 2.6 Tg C per every 10 Tg C increase in fossil fuel emissions, or approximately a quarter. This relationship varies by land cover type with variation explained ranging from 0% to 52% for the 12 out of 15 linear regressions that were significant (table 3). Fossil fuel emissions explained 31%, 22% and 21% of the variation in biomass burning for woody savannas, savannas and deciduous broadleaf forests, respectively. The significant inverse relationship between the variables is consistent across most land cover types, 11 out of 12, with the exception of closed shrublands (figure 4 and table 3).

4. Discussion

Humans are the planet's keystone species for fire [41], and if they change how they manage combustion—as landscape burning or contained, industrial burning of fossil fuels—then there will be likely cascading effects. At a global scale, this study demonstrates that average annual biomass burning emissions decline as fossil fuel emissions increase (between 1997 and 2010). Eight per cent of the variation in biomass burning emissions globally can be explained by fossil fuel emissions. This is an apparently weak relationship (adj.

Table 1. Summary of mean (Tg C yr^{-1}), standard deviation (Tg C yr^{-1}) and coefficient of variation (%) of emissions from biomass burning (bb) and fossil fuels (ff) by land cover type and area (M km^{-2}).

	biomass burning					fossil fuels						
land cover	mean (Tg C yr^{-1})	s.d.	CV (%)	% of global total	Tg C Mkm^{-2}	mean (Tg C yr^{-1})	s.d.	CV (%)	% of global total	Tg C Mkm^{-2}	area (million km^2)	ratio ff:bb
evergreen needleleaf forest	26.0	11.3	43.6	1.18	8.0	79.3	2.1	2.6	1.23	24.3	3.3	3.1
evergreen broadleaf forest	486.7	257.9	53.0	22.15	35.1	313.8	53.3	17.0	4.87	22.6	13.9	0.6
deciduous needleleaf forest	18.0	21.8	121.2	0.82	13.0	15.8	0.7	4.2	0.25	11.4	1.4	0.9
deciduous broadleaf forest	14.5	2.4	16.4	0.66	12.5	191.0	5.5	2.9	2.96	163.6	1.2	13.1
mixed forest	65.8	38.3	58.2	2.99	6.7	1191.5	131.3	11.0	18.50	121.6	9.8	18.1
closed shrublands	0.1	0.1	77.7	0.00	1.1	0.2	0.0	6.4	0.00	2.7	0.1	2.4
open shrublands	71.4	25.9	36.2	3.25	3.3	340.3	26.7	7.9	5.28	15.6	21.8	4.8
woody savannas	776.4	59.7	7.7	35.34	77.7	369.8	54.6	14.8	5.74	37.0	10.0	0.5
savannas	467.0	72.6	15.5	21.26	46.2	89.7	7.8	8.7	1.39	8.9	10.1	0.2
grasslands	71.0	14.1	19.8	3.23	3.9	571.2	78.8	13.8	8.87	31.6	18.1	8.0
permanent wetlands	8.8	3.9	44.4	0.40	11.3	25.7	1.1	4.4	0.40	32.8	0.8	2.9
croplands	59.9	7.4	12.4	2.72	5.0	1994.5	303.3	15.2	30.96	165.4	12.1	33.3
urban and built-up	0.3	0.2	77.9	0.01	3.4	144.3	3.8	2.6	2.24	1833.1	0.1	544.4
cropland/natural vegetation mosaic	130.5	33.0	25.3	5.94	20.1	737.6	37.9	5.1	11.45	113.3	6.5	5.7
barren or sparsely vegetated	0.4	0.2	39.1	0.02	0.0	377.0	80.0	21.2	5.85	19.7	19.1	1002.6
global	2236.0	346.2	15.5			7314.3	834.0	11.4			509.3	3.3

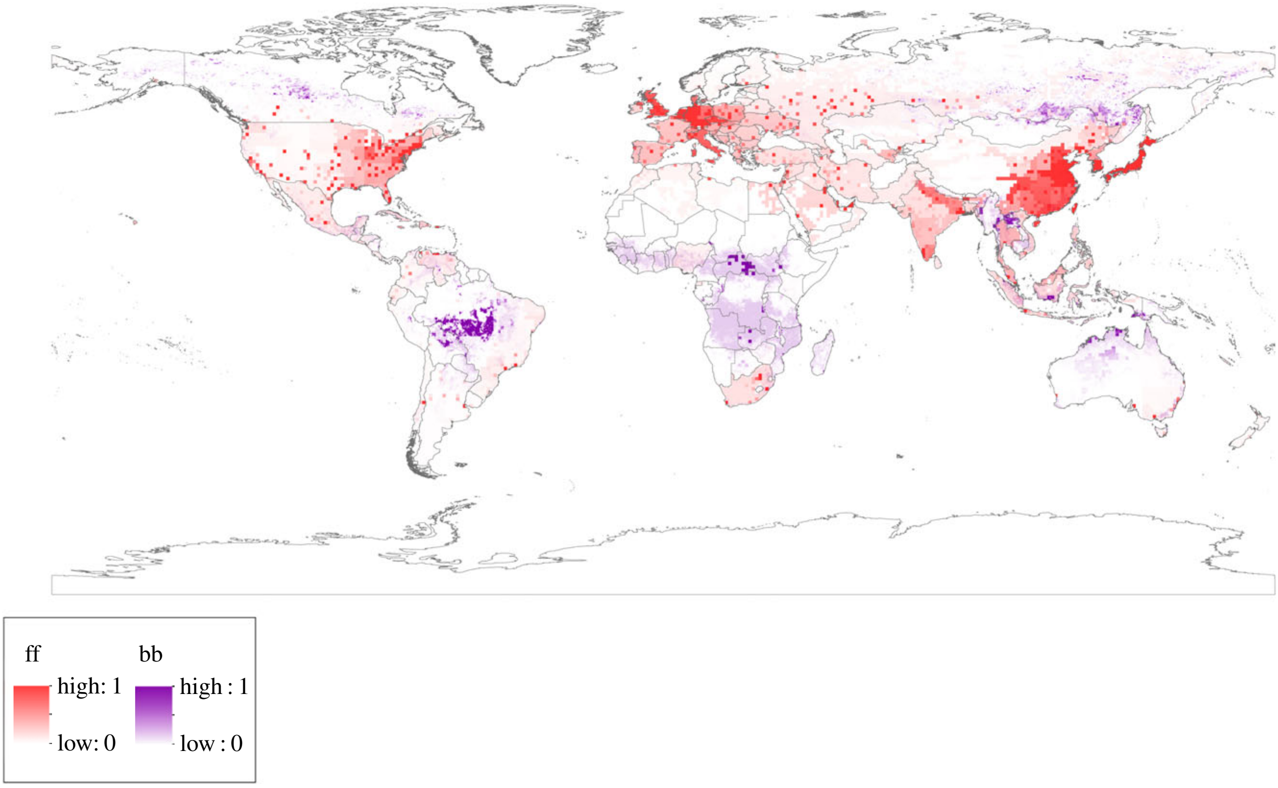

Figure 1. Scaled average global emissions from biomass burning (bb, purple) and fossil fuels (ff, red) from 1997 to 2010. Average global emissions by grid cell from 1997 to 2010 were scaled from zero to one by dividing each cell's emissions by the maximum emissions across all cells. Original data sources: Global Fire Emissions Database (GFED; http://www.globalfiredata.org/data.html) and Carbon Dioxide Information Analysis Center (CDIAC; http://cdiac.ornl.gov/). The CDIAC data (1.0 degree resolution) were disaggregated to match the spatial resolution of the GFED4s data (0.25 degree resolution).

Table 2. Area in millions of square-kilometres (Mkm^2) occupied by each combination of biomass burning (bb) and fossil fuel (ff) emissions classes: zero, low, medium, and high.

bb class	ff class	area (M km^2)
zero	zero	19.8
med	med	17.2
zero	med	11.0
med	high	10.8
high	low	10.3
low	med	9.3
high	med	7.9
med	zero	7.5
med	low	7.2
zero	low	5.1
low	high	4.9
high	zero	4.2
low	zero	4.0
low	low	3.1
zero	high	2.8
high	high	2.2

$R^2 = 0.08$); however, human predictor variables generally are secondary to the strength of climate variables in global fire models [17,19,25]. Further, the strength of this relationship varies markedly by land cover type, with greater explanatory power in woody savannas, savannas and deciduous broadleaf forests (adj. $R^2 = 0.31$, 0.22 and 0.21, respectively; table 3). These three land covers represent 20% of the global vegetated land surface (approx. 21 million km^2 out of approx. 109 million km^2; table 1). Deciduous broadleaf forests, such as the eastern US and Europe, have a long history of fire suppression that accompanied more industrial forms of combustion [42,43], making fossil fuel burning a predictor of reduced levels of landscape fire. Evergreen needleleaf forests (e.g. the boreal), however, showed a non-significant relationship between fossil fuel and biomass burning. These forests are generally less populated areas that are dominated by lighting-started fires and therefore this link would be expected to be poor [44]. Tropical evergreen broadleaf forests, such as the Amazon, similarly had a poor relationship between fossil fuel and biomass burning. Humid tropical forests have only experienced substantial agricultural frontier expansion in the past few decades [45], and it most likely will take several more decades for the fires associated with deforestation and subsequent land management to decline as industrialization takes root [46]. Within this 14 year period, areas that have both high levels of landscape biomass and fossil fuel burning are rare, representing only 1.5% of the global land surface (table 2). One example comes from Indonesia, which ranked 15th among fossil-fuel-emitting nations in 2008 [47] and had some of the highest biomass burning emissions from tropical peatland fires during this period [37,48]. Areas of transition, which have moderate fossil fuel burning and moderate biomass burning, represent 12% of the land surface, and include places such as the coastal forests of Brazil where the majority of the country's population lives and agricultural burning is still common practice (figure 2 and table 2).

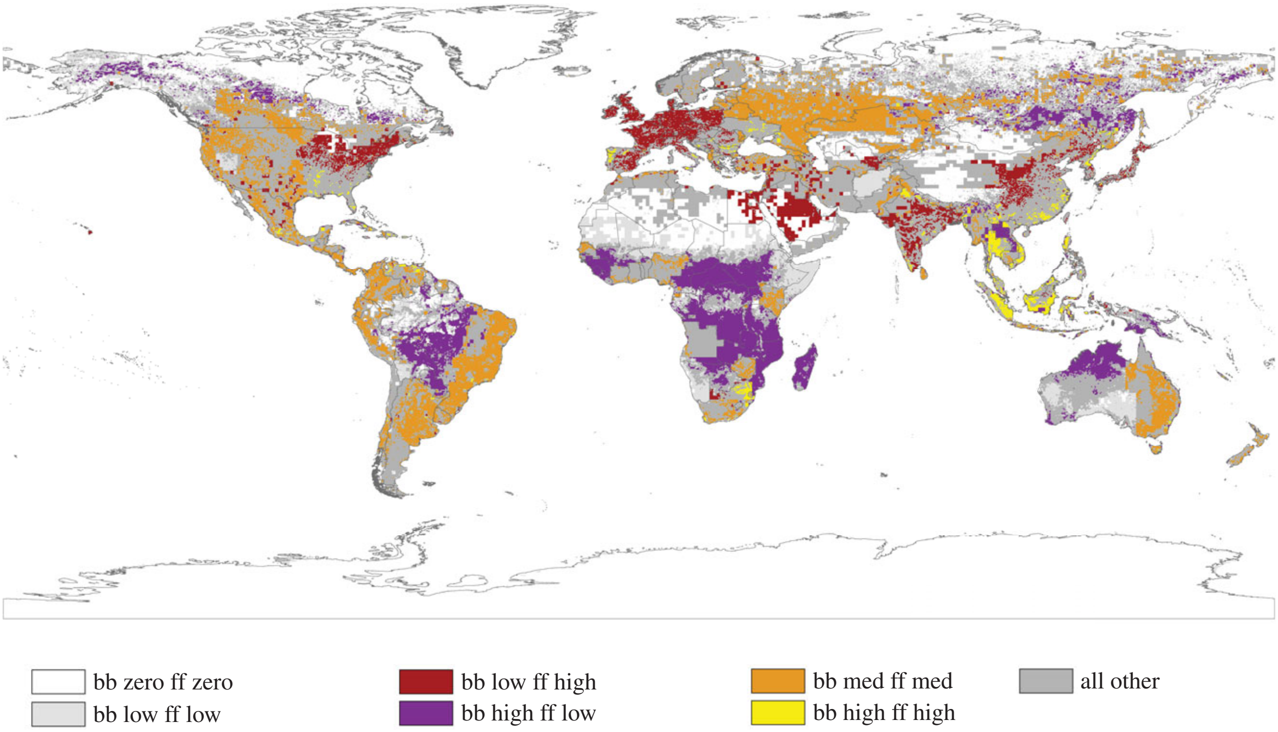

Figure 2. Categories of scaled average biomass burning (bb) and fossil fuel (ff) emissions (1997–2010), including zero, low, medium and high. Grid cells were re-classified according to four categories of scaled emissions: zero, low, medium and high for biomass burning and fossil fuels, where the zero class corresponds to a scaled value of zero, low are values between zero and the first quantile of scaled data (after zeros were removed), medium are values between the first and third quantile and high are values between the third quantile and one. For simplification, several categories were combined. The bb low/ff low category combines areas where emissions from biomass or fossil fuel burning were either low or zero, but where at least one was greater than zero (bb low/ff zero, bb low/ff low and bb zero/ff low). The bb high/ff low category indicates high bb and either low or zero ff. The bb low/ff high category indicates either low or zero bb and high ff. The 'all other' category includes areas where emissions from either (but not both) fossil fuel or biomass burning were medium (bb zero/ff med, bb low/ff med, bb med/ff zero, bb med/ff low, bb med/ff high and bb high/ff med).

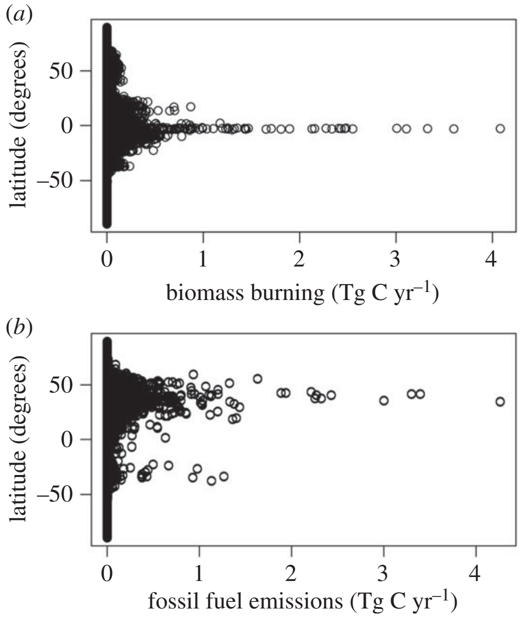

Figure 3. Mean annual emissions (Tg C yr^{-1}) from 1997 to 2010 of each grid cell versus grid cell latitude for (*a*) biomass burning and (*b*) fossil fuel combustion. Because the area of the grid cells changes with latitude, emissions per grid cell were multiplied by the area (m^2) that each grid cell occupies on the ground.

As demonstrated here, the inverse relationship between fossil fuel and biomass burning is an important phenomenon and should be captured in models of the anthropogenic drivers of global fire. Previous global fire modelling efforts have included human population density, cropland and pasture lands, GDP, road density and compilations of variables captured by the human footprint [15,17–19,25]. This study suggests that incorporation of fossil fuel emissions into global fire models may improve prediction by better representing the shift from open landscape burning to more industrialized forms of combustion.

Although this study is based on a relatively long satellite-based record, one important limitation is the short temporal scale (14 years) relative to the time period over which such a transition may take place (likely 50–100 years or more). This study is best considered as a chronosequence that captures places in different phases of the transition, rather than places where we can observe the transition in a 14 year period. Another limitation is that the separate contribution of natural fires, as distinct from human-started fires, is unknown in the global biomass burning emissions estimates. Moreover, we do not account for the varied ability of humans to alter fire regimes by ecosystem. Here, we use fossil fuel emissions as a metric of industrialized combustion that has substituted landscape biomass burning. There may be other important predictors of human-started fires in the landscape, such as (i) vulnerable infrastructure (e.g. houses, fences, etc.) that would predict more constrained use of fire or (ii) the cost of mechanically removing agricultural waste, compared with using fire. The challenge of future studies is to find globally available data that can serve as better predictors of human-induced changes to the global fire cycle.

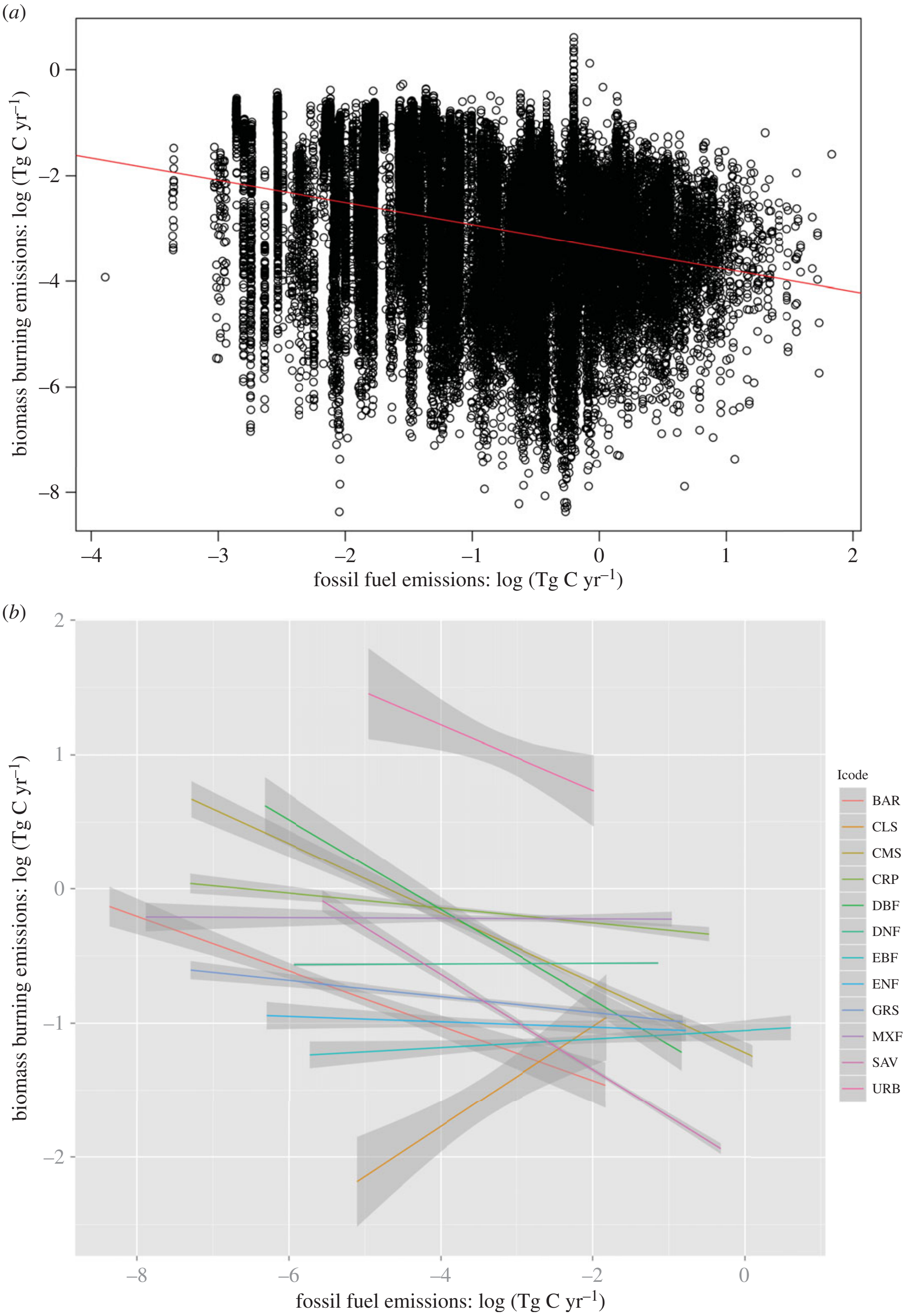

Figure 4. (*a*) Linear regression of mean annual global fossil fuel emissions log (Tg C yr^{-1}) as a predictor of global biomass burning emissions log (Tg C yr^{-1}) from 1997 to 2010; (*b*) linear regression of mean annual fossil fuel emissions log (Tg C yr^{-1}) as a predictor of biomass burning emissions log (Tg C yr^{-1}) by land cover (lcode; 1997–2010); shading indicates a Loess smoothing function. Because the area of the grid cells changes with latitude, emissions per grid cell were multiplied by the area (m^2) that each grid cell occupies on the ground (See table 3 for definitions of land cover type codes.).

(a) The ‘combustion ladder’

At a household scale, development theory predicts that as socioeconomic status increases, fuels that are inefficient, cheaper and more polluting (e.g. from smoke) are abandoned, termed the ‘energy ladder’ [49,50]. Fuels that are ‘higher’ on the ladder, such as liquid and gaseous fuels, tend to replace fuels that are ‘lower’, such as dung, fuel wood and charcoal [51]. Beyond energy use, this concept of transitions can help explain different phases of human use of fire at the landscape-level. We expect that landscape fires set for preservation of livelihoods will be replaced by industrial combustion that is more efficient, less risky and less polluting in terms of localized smoke pollution. We term this concept the ‘combustion ladder’, where fire use and fire management shift towards using more efficient, clean and safer forms of combustion that may ultimately exclude open use of fire in the landscape. It is important to note, however, that the net effect of industrialized combustion is much more polluting in terms of carbon emissions; here, we show that it is three times greater over

Table 3. Summary of linear regression models of log biomass burning versus log fossil fuel emissions by land cover type. n.s., not significant.

land cover	land cover code	slope	residual standard error	*F*-value	d.f.	*p*-value	adj. *R*-squared
1. Permanent wetlands	PWL	−0.81	1.02	25.48	90	<0.0001	0.21
2. Urban and built-up	URB	−0.78	0.66	7.29	31	0.01114	0.16
3. Woody savannas	WDS	−0.63	0.96	1557.63	3519	<0.0001	0.31
4. Deciduous broadleaf forest	DBF	−0.62	0.98	122.75	466	<0.0001	0.21
5. Open shrublands	OPS	−0.61	1.26	531.13	4361	<0.0001	0.11
6. Savannas	SAV	−0.61	0.72	1006.55	3647	<0.0001	0.22
7. Cropland/natural vegetation mosaic	CMS	−0.4	0.98	320.14	2798	<0.0001	0.10
8. Barren or sparsely vegetated	BAR	−0.37	1.09	75.73	942	<0.0001	0.07
9. Grasslands	GRS	−0.15	1.15	44.52	5049	<0.0001	0.01
10. Croplands	CRP	−0.11	0.94	36.57	5725	<0.0001	0.01
11. Evergreen needleleaf forest	ENF	−0.07	1	1.57	1094	0.20985	n.s.
12. Mixed forest	MXF	−0.01	0.92	0.04	3154	0.84	n.s.
13. Evergreen broadleaf forest	EBF	0.04	0.99	4.57	3508	0.03257	0
14. Closed shrublands	CLS	1.48	0.66	20.86	17	0.00027	0.52
15. Deciduous needleleaf forest	DNF	2.53	0.93	1.43	228	0.23275	n.s.
16. Global	GLB	−0.42	1.25	2955.72	34 657	<0.0001	0.08

the period from 1997 to 2010—greatly exceeding the capacity of vegetation and oceans to uptake that carbon [28].

The concept of a 'combustion ladder' may explain why contemporary biomass burning rates in ice core reconstructions from the Southern Hemisphere [52,53] and the global charcoal record [54,55] have been shown to be comparable to or lower than pre-industrial biomass burning rates [56]. Marlon *et al.* [54] describe a sharp decline in fire after 1870 in the global charcoal record, but cannot attribute this reduction to air temperatures, which have increased during the industrial period. Wang *et al.* [53] show biomass burning in the Southern Hemisphere, as observed through ice core reconstructions, has declined by 70% from the late 1800s to today. Given our results, we hypothesize that this observed decline is related to the shift from open landscape burning to maintain livelihoods to more industrialized forms of combustion and a companion loss of fire in more intensive and mechanized agricultural systems.

One important consequence of the transition to more industrialized forms of combustion in flammable ecosystems is that depopulated and unmanaged landscapes are left to accumulate fuels. When fires do occur, they are likely to be larger and more severe, as observed in Mediterranean ecosystems experiencing urban migration and agricultural abandonment over the past few decades [57,58]. Indeed, one of the few areas with high biomass burning and fossil fuel emissions that we observed was in Portugal and Spain (figure 3). Woody savannas and savannas had some of the stronger inverse relationships between fossil fuel combustion and biomass burning. However, as many African nations industrialize, it is unlikely that there would be a complete loss of open landscape burning in the tropical savannas, unless people also drastically change land cover and thereby reduce grass fuels [59]. These examples highlight that the strength of the relationship between fossil fuel combustion and biomass burning may vary across land cover types, reflecting variation in how responsive natural fire regimes are to anthropogenic ignitions and fuel restructuring.

(b) Unique moment in the fire history of our planet

The satellite record over the past few decades captures a unique moment in the fire history of our planet. The Anthropocene marks a period of time where human agency has caused substantial changes to fundamental Earth system processes [60,61], including global fire regimes. Traditional fire management by indigenous groups only remains in small fragments [62–65], compared with what was likely the predominant form of fire management across many parts of the globe. Frontier fire in tropical forests, which is used to remove unwanted biomass through the deforestation process, has been a substantial contributor to biomass burning emissions over the past few decades [12,35], but likely is only a temporary use of fire in the land conversion process. Agriculture and pasture burning are fundamental tools in land management [10], which may shift as technologies from more mechanized agriculture are available. Urban centres, which now hold more than half of the world's global population [66], have fundamentally removed landscape fire—a concept that is notably absent from frameworks on urban ecology [67]. In flammable ecosystems, fire management is attempting to put fire back into ecosystems that have had much more frequent fire in the past [68]. Whether the current picture of fire represents historical or future patterns is best placed in context of thinking of the land surface as a palimpsest, an ancient papyrus text with a memory, that reflects previous use of the landscape, but ultimately represents a new story about the human use of combustion.

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