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Global Pyrogenic Carbon Production During Recent Decades Has Created the Potential for a Large, Long-Term Sink of Atmospheric CO_2

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Key Points:
- We present two modeling approaches to estimate the spatiotemporal dynamics of global pyrogenic carbon (PyC) produced from fires
- We calculate global PyC production from fires as 153.4 ± 18.7 and 49.5 ± 4.9 Tg C/year based on the estimates from GFED4s and TEM6
- The magnitude of PyC produced by fires represents a potentially significant long-term sink of atmospheric CO_2

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Abstract Fires play an important role in the terrestrial biosphere carbon cycle, not only through direct carbon release but also contributing to a potential long-term storage as pyrogenic carbon (PyC). PyC is formed through fires, and, because it may resist further biological and chemical degradation, is more stable in soil and sediment than original biomass. At the global scale, contributions of fires to both atmospheric CO_2 emissions and PyC accumulation are potentially large but difficult to estimate. Our analysis was based on existing simulation results from two different modeling approaches (Global Fire Emissions Database version 4 [GFED4s] and Terrestrial Ecosystem Model version 6 [TEM6]) that used global area burned data to provide recent, retrospective estimates of CO_2 emissions from vegetation combustion, together with published, biome- and continental-scale conversion ratios that relate CO_2 emissions to PyC production (PyC/CO_2) during combustion. The estimates of global CO_2 emissions from fires differed substantially between the two models' results. GFED4s estimated 2,041 Tg C/year during the 2000–2016 time period, whereas the TEM6 estimate was considerably lower at 643 Tg C/year from 2000 to 2010. Global PyC production estimates from fires were 153.4 ± 18.7 and 49.5 ± 4.9 Tg C/year based on the emission estimates from GFED4s and TEM6, respectively. Our results suggest that African tropical savanna fires produced the largest amount of CO_2 emissions and PyC among global biomes, the most significant interannual variations in CO_2 emissions and PyC production were found in tropical forests, and the magnitude of PyC produced by fires each year represented a potentially significant long-term sink of atmospheric CO_2.

1. Introduction

Fires, as worldwide ecological disturbances, appeared in the geological record soon after the appearance of terrestrial plants. Fires strongly influence the terrestrial carbon cycle across a broad range of spatial and temporal scales by transferring carbon between ecosystem pools and the atmosphere, as well as through the legacy effects of resetting succession (Chen et al., 2017; Giglio et al., 2013). Fires directly convert carbon stored in biomass, including litter and soil organic matter, to gaseous and particulate forms, which are released to the atmosphere (Forbes et al., 2006). These gases not only consist primarily (>90%) of CO_2 but also include CO, CH_4, and CH_3Cl (Crutzen & Andreae, 1990). At the same time, a portion of organic carbon is thermochemically converted to recalcitrant pyrogenic carbon (PyC, also named as black carbon, charred biomass, soot, or colloquially as charcoal), which is formed from the combustion of organic matter through biomass burning (Bird et al., 2017; Wagner et al., 2018).

PyC includes a range of particle sizes, from mainly macroscopic charcoal and partially charred vegetation material that remains on site to small particles in smoke that may remain in the atmosphere for over a week and thus transported far from the site of origin (Cooke & Wilson, 1996). Due to its more chemically and biologically stable properties, when compared to original biomass (Kuzyakov et al., 2014; Santín et al., 2015), PyC may have a relatively long residence time (e.g., Cotrufo et al., 2016; Singh et al., 2014). Assuming the postfire carbon can recover to the prefire status, PyC may thus serve as a long-term, stable sink that is distributed globally via fluvial and atmospheric transport to become a ubiquitous component in soil, lacustrine, and marine sediment (Santín et al., 2016).

Fuel type, fire intensity, and weather conditions codetermine PyC production during fires (Czimczik et al., 2005; Schmidt & Noack, 2000). Previous studies have explored PyC production rates across various biomes; these rates may be estimated in one of the three ways: (1) the ratio of carbon contained in PyC to that

directly released as CO_2 through a burning event (PyC/CO_2; e.g., Hao et al., 1990; Kuhlbusch & Crutzen, 1996); (2) the ratio of carbon contained in PyC to the carbon exposed to the fire (PyC/C exposed; e.g., Santín et al., 2015); or (3) the ratio of carbon contained in PyC to the carbon consumed through burning (PyC/C consumed; e.g., Forbes et al., 2006; Santín et al., 2016). If these ratios were relatively constant within a biome, and the denominators were reasonably estimated, PyC production from fires could be quantified at the biome, continental, and global scales (e.g. Crutzen & Andreae, 1990; Forbes et al., 2006; Kuhlbusch et al., 1996; Preston & Schmidt, 2006; Santín et al., 2016).

Given the substantial impact of fires on the global carbon cycle (van der Werf et al., 2017), improved estimates of PyC production are necessary to better understand, quantify, and model the global carbon cycle. Several previous studies have estimated PyC production at the global scale (e.g., Bird et al., 2015; Kuhlbusch & Crutzen, 1995; Santín et al., 2016), but none have incorporated the full set of biome-specific conversion ratios to characterize and quantify the temporally and spatially explicit patterns of PyC production from global vegetation burning. The objectives of our study were to (1) update the estimate of PyC produced by global fires using detailed, biome-scale PyC-carbon ratios obtained from previous studies; and (2) present the spatiotemporal and interannual variations of CO_2 emissions and PyC production from global fires in the period of 2000–2016.

2. Materials and Methods

2.1. Estimates for Fire-Caused CO_2 Emissions

The magnitude and rate of carbon emissions to the atmosphere from fires over large regions has been quantified and extrapolated based on inventories and ecosystem models (e.g., French et al., 2011; Kasischke et al., 2013). Using the inventory-based burned area data along with meteorological information, vegetation characteristics, and emission factors for different land ecosystems, such approaches can estimate the CO_2 released from global fires (Giglio et al., 2013). Here we use existing estimates of fire emissions from previous simulation results from two distinct, process-based carbon cycle models, namely, the Global Fire Emissions Database (van der Werf et al., 2017) and the Terrestrial Ecosystem Model (Hayes et al., 2011). Because neither model directly estimates PyC production from fires, we used the CO_2 emissions estimates provided by these model results, along with published biome-specific PyC/CO_2 ratios, to estimate the spatial and temporal patterns of global PyC production.

2.1.1. Fire-Caused CO_2 Emission From GFED4s

The Global Fire Emissions Database version 4 (GFED4s; Giglio et al., 2013; van der Werf et al., 2010) provides a framework for assessing the impact of fires on the terrestrial biosphere carbon cycle, including global burned area and monthly emissions during 1997–2016. The monthly emissions are estimated based on observed burned area data and active fire information classified from Moderate Resolution Imaging Spectroradiometer imagery, land cover characteristics, and meteorological data (Giglio et al., 2013). Carbon in biomass and soil organic matter representing fuels in combustion are simulated with a revised version of the Carnegie-Ames-Stanford approach biogeochemical model (van der Werf et al., 2017). In the latest version, GFED4s (van der Werf et al., 2017), "s" means that burned area caused by small fires estimated by models is included in this database, which provides global CO_2 emissions at monthly time step and 0.25° spatial resolution. In our analysis, the worldwide monthly CO_2 emissions from 2000 to 2016 were used to estimate PyC resulting from fires.

2.1.2. Fire-Caused CO_2 Emission From TEM6

The Terrestrial Ecosystem Model version 6 (TEM6; Chen et al., 2017; Hayes et al., 2011) is within the class of process-based terrestrial biosphere models (McGuire et al., 2000) that simulate the dynamics of carbon, nitrogen, and water through plants and soils as determined by climate, atmospheric chemistry, land use, and disturbances (Huntzinger et al., 2017; McGuire et al., 2000). TEM6 has been used to examine terrestrial carbon dynamics at various spatial scales and monthly temporal resolution (e.g., Hayes et al., 2011). It was modified by Balshi et al. (2007) to simulate the changes of carbon pools resulting from fires in pan-boreal region and further modified and applied to estimate the carbon fluxes and storage from burning over large regions (e.g., Chen et al., 2017). In our study, TEM6 provided CO_2 emissions released from fires at monthly time step and 0.5° spatial resolution from 2000 to 2010 based on the global simulation results developed for the Multi-Scale Synthesis and Terrestrial Model Intercomparison Project (Huntzinger et al., 2013; Wei et al., 2014).

2.2. PyC Estimation

The two modeling approaches used here estimated carbon directly released by fires as CO_2. Published relationships between PyC and CO_2, specific to each biome of interest, are described below and used to estimate PyC from fires in this analysis. Because several published studies did not present the conversion ratio PyC/CO_2, we calculated it from their results, using equation (1).

$$PyC/CO_2 = \frac{PosF\_PyC - PreF\_PyC}{[(PosF\_C + PosF\_PyC) - (PreF\_C + PreF\_PyC)] * EF} \quad (1)$$

where PreF_C is the total prefire carbon, PreF_PyC is the total prefire PyC, PosF_C is the total postfire carbon, PosF_PyC is the total postfire PyC, and EF is a constant emission factor, representing the percentage of C in released CO_2 of total released carbon. Given that the EF is ~90% (e.g., Crutzen & Andreae, 1990; Forbes et al., 2006), we used 0.9 in the calculation.

Based on the set of PyC/CO_2 ratios that we synthesized across various land ecosystems, we divided the global terrestrial biosphere into seven biomes (Figure 1). The biome information was obtained using the Terrestrial Ecoregions of the World Map (Olson et al., 2001; http://www.worldwildlife.org/science/data/item1875.html) and was resampled at both 0.25 × 0.25 (GFED4s) and 0.5 × 0.5 (TEM6) degree resolutions to estimate the PyC production from CO_2 emissions. In addition, we further aggregated biome regions to five continents, namely, Africa, Australia, Eurasia, North America, and South America.

2.2.1. Boreal Forest

Santín et al. (2015) quantified the prefire and postfire fuel and PyC in the boreal forest under the experimental fire, and they concluded that the PyC/CO_2 ratio was 38.1%. Thompson et al. (2016) used laboratory burning for masticated wood fuel particles collected from the boreal forest and concluded a PyC/CO_2 ratio of 0.3–1.4%. Czimczik et al. (2003) analyzed elemental concentrations in both unburned and burned samples from a naturally occurring boreal surface fire in west Siberia, concluding that the PyC/CO_2 ratio was 1.9%. Kuhlbusch and Crutzen (1995) sampled organic materials from various biomes and combusted them in the laboratory to measure the PyC/CO_2 ratios in various biome regions. Their laboratory analyses of boreal forest determined a PyC/CO_2 ratio of 5.0–7.0%. It should be noted that this study focused on particles with an average diameter of 40 μm, meaning that smaller PyC particles may have been omitted.

2.2.2. Temperate Forest

In an Australian temperate forest, Graetz and Skjemstad (2003) applied a quantitative framework of charcoal redistribution to estimate the PyC ratios. By monitoring the quantity of PyC in situ and moved by water before and after managed and unmanaged fires, they estimated a PyC/CO_2 ratio of 6.4–11.3% (Table 1). However, their calculations ignored the small PyC particles, because they assumed this to be a very small component. Jenkins et al. (2016) investigated both the charcoal and ash created by planned burning in an Australian forest and reported a PyC/CO_2 ratio of 5.1%. Finkral et al. (2012) sampled the slash pile before and after a prescribed burning in northern Arizona, USA, and measured the char particles. Their results indicated a PyC/CO_2 ratio of 1.1–5.1%. Miesel et al. (2018) quantified the PyC production and carbon losses by five wildfires in the California mixed-conifer forest. They reported a PyC/CO_2 ratio of 4.1%. Comery (1981) analyzed residues from a temperate conifer forest in Florida before and after prescribed burning, reporting a PyC/CO_2 ratio of 9.9%. Brewer et al. (2013) used laboratory fire to burn masticated fuels collected from Idaho, USA, and measured the postfire charred residues. This analysis suggested a PyC/CO_2 ratio of 11.8–12.7%. Pingree et al. (2012) compared the charcoal quantity in prewildfire and postwildfire soil and fuel in southwest Oregon, USA, and their results suggested a PyC/CO_2 ratio of 1.1–8.9%. Eckmeier et al. (2007) used experimental fires to burn slash of a temperate deciduous forest in Germany and then analyzed the fire-created charcoal. Their analysis suggested a PyC/CO_2 ratio of 8.9%. Kuhlbusch and Crutzen (1995) applied the lab-based method to measure the PyC conversion ratio for the temperate forest biome, reporting that the PyC/CO_2 ratio ranged from 5.0% to 7.0%.

2.2.3. Tropical Forest

Fearnside et al. (1993) sampled PyC materials after a slash-and-burn deforestation fire in the Amazon rainforest, mainly by visually assessing charcoal content, and reported a PyC/CO_2 ratio of 10.8% (Table 1). Barbosa and Fearnside (1996) resampled the postfire residues in Amazon fires and updated this ratio to 2.9%. Then, Fearnside et al. (1999) reported a ratio of 3.3% in the Amazon. In another study, Fearnside et al. (2001) updated this ratio to 4.5%. In a later study, Fearnside et al. (2007) estimated a similar ratio of 4.6%. Graça et al. (1999)

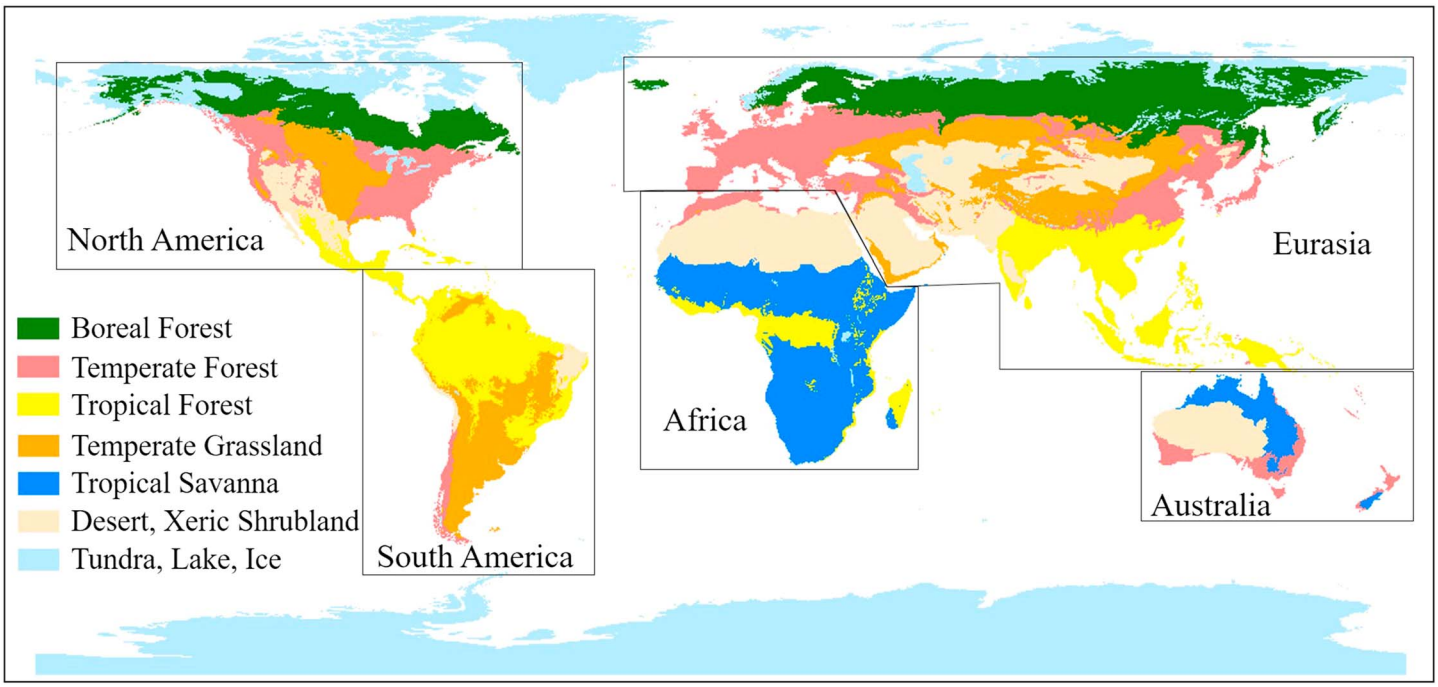

Figure 1. The seven global biomes used in this study, aggregated to five continental-scale regions.

measured postfire residues in the soil after a slash-and-burn deforestation fire in the Amazon rainforest and estimated the PyC/CO_2 ratio to be 10.2%. Kauffman et al. (1995) quantified the total aboveground biomass and charcoal before and after a slash-and-burn deforestation fire in an Amazon tropical moist forest, and their analysis suggested a PyC/CO_2 ratio of 8.4–19.7%. Righi et al. (2009) measured the total aboveground biomass and charcoal in each plot before and then again after prescribed burning, reporting a PyC/CO_2 ratio of 14.0%. Kuhlbusch and Crutzen (1995) used laboratory analyses to determine that the PyC/CO_2 ratio ranged from 5.0% to 7.0% for tropical forest at the global scale.

2.2.4. Temperate Grassland

Using the inventory data provided by the Food and Agriculture Organization of the United Nations, Hao et al. (1990) reported a PyC/CO_2 ratio of 0.3% (Table 1) across the Asian steppe; however, this ratio increased to 3.7% in North American grassland. Clay and Worrall (2011) investigated char production from a series of prescribed burns from moorland in the Peak District, UK. Their results indicated a PyC/CO_2 ratio of 5.0%. Worrall et al. (2013) applied the same method and updated this ratio to 3.0% for this area. Lobert et al. (1991) sampled organic materials from temperate grassland and burned them in the laboratory. They estimated a PyC/CO_2 ratio of 6.0%. In temperate grasslands, based on lab experiments, Kuhlbusch and Crutzen (1995) estimated the PyC/CO_2 ratio to be in the range from 1.3% to 2.9% globally. In a later study, Kuhlbusch and Crutzen (1996) updated this ratio to 1.3%.

2.2.5. Tropical Savanna

Delmas et al. (1991) and Lacaux et al. (1993) reported PyC/CO_2 ratios of 11.8% and 6.2%, respectively, through measuring the char particles in both prefire and postfire residues in Africa (Table 1). With inventory data, Hao et al. (1990) reported a PyC/CO_2 ratio of 11.6% in African tropical savanna ecosystems, and this ratio decreased to 2.0% in Australian tropical savanna. Kuhlbusch et al. (1996) quantified the PyC formed in the residues of savanna fires on six experimental sites in southern Africa and determined a PyC/CO_2 ratio of 15.4%. Menaut et al. (1991) measured the visual char created from savanna fires in West Africa and concluded a PyC/CO_2 ratio of 1.6%. Hurst et al. (1994) used physical separation of PyC particles following a tropical savanna fire to obtain a PyC/CO_2 ratio of 1.3% in Australia. Saiz et al. (2014) used controlled field burning experiments in four savanna sites in northeastern Australia and quantified the production of visual PyC. Their results suggested a PyC/CO_2 ratio of 21.2%. Kuhlbusch and Crutzen (1995) estimated a PyC/CO_2 ratio of 1.3–2.9% globally through their laboratory-based experiment.

Table 1
Pyrogenic carbon (PyC) Conversion Ratios (PyC/CO_2) From Published Studies

Study location	PyC/CO_2 (%)	Type of fire	Fuel type	Type of PyC	Reference
Boreal forest					
Canada	38.1	Experimental	All fuels	Charred mass	Santín et al. (2015)
Canada	0.3–1.4	Laboratory	Masticated fuel	Total	Thompson et al. (2016)
Siberia	1.9	Wildfire	Forest floor	Total	Czimczik et al. (2003)
Global	5.0–7.0	Laboratory	All fuels	≥40 μm	Kuhlbusch and Crutzen (1995)
Temperate forest					
Australia	6.4–11.3	All[a]	Surface fuel	Total	Graetz and Skjemstad (2003)
Australia	5.1	Prescribed	Surface fuel	Charcoal, ash	Jenkins et al. (2016)
Arizona, USA	1.1–5.1	Prescribed	Slash pile	Total	Finkral et al. (2012)
California, USA	4.1	Wildfire	All fuels	Total	Miesel et al. (2018)
Florida, USA	9.9	Prescribed	Surface fuel	Visual charcoal	Comery (1981)
Idaho, USA	11.8–12.7	Laboratory	All fuels	Charcoal, ash	Brewer et al. (2013)
Oregon, USA	1.1–8.9	Prescribed	Woody fuels	>2000 μm	Pingree et al. (2012)
Germany	8.9	Experimental	Slash pile	≥1 mm	Eckmeier et al. (2007)
Global	5.0–7.0	Laboratory	All fuels	≥40 μm	Kuhlbusch and Crutzen (1995)
Tropical forest					
Amazon	10.8	Prescribed	Slash pile	Visual charcoal	Fearnside et al. (1993)
Amazon	2.9	Prescribed	Slash pile	Visual charcoal	Barbosa and Fearnside (1996)
Amazon	3.3	Prescribed	Slash pile	Visual charcoal	Fearnside et al. (1999)
Amazon	4.5	Prescribed	Slash pile	Visual charcoal	Fearnside et al. (2001)
Amazon	4.6	Prescribed	Slash pile	Visual charcoal	Fearnside et al. (2007)
Amazon	10.2	Experimental	Slash pile	Charcoal, ash	Graça et al. (1999)
Amazon	8.4–19.7	Prescribed	Woody debris	Ash	Kauffman et al. (1995)
Amazon	14.0	Prescribed	Slash pile	Visual charcoal	Righi et al. (2009)
Global	5.0–7.0	Laboratory	All fuels	≥40 μm	Kuhlbusch and Crutzen (1995)
Temperate grassland					
America	3.7	Wildfire	Surface fuel	Visual charcoal	Hao et al. (1990)
Asia	0.3	Wildfire	Surface fuel	Visual charcoal	Hao et al. (1990)
UK	5.0	Prescribed	Surface fuel	Total	Clay and Worrall (2011)
UK	3.0	Laboratory	Surface fuel	Total	Worrall et al. (2013)
Global	6.0	Laboratory	Surface fuel	Ash	Lobert et al. (1991)
Global	1.3	Laboratory	All fuels	Total	Kuhlbusch et al. (1996)
Global	1.3–2.9	Laboratory	All fuels	≥40 μm	Kuhlbusch and Crutzen (1995)
Tropical savanna					
Africa	11.8	Wildfire	Surface fuel	Visual charcoal	Delmas et al. (1991)
Africa	11.6	Wildfire	Surface fuel	Visual charcoal	Hao et al. (1990)
Africa	15.4	Wildfire	Surface fuel	Visual charcoal	Kuhlbusch et al. (1996)
Africa	6.2	Wildfire	Surface fuel	Visual charcoal	Lacaux et al. (1993)
Africa	1.6	Wildfire	Surface fuel	Visual charcoal	Menaut et al. (1991)
Australia	4.0	Wildfire	Surface fuel	Total	Graetz and Skjemstad (2003)
Australia	2.0	Wildfire	Surface fuel	Visual charcoal	Hao et al. (1990)
Australia	1.3	Wildfire	Surface fuel	Visual charcoal	Hurst et al. (1994)
Australia	21.2	Experimental	Surface fuel	Visual charcoal	Saiz et al. (2014)
Global	1.3–2.9	Laboratory	All fuels	≥40 μm	Kuhlbusch and Crutzen (1995)

[a]Managed and unmanaged forest fires.

2.2.6. Desert, Xeric Shrubland and Tundra

The fuel type and fire weather in desert, xeric shrubland ecosystems differ substantially from those of other terrestrial ecosystems. Perhaps partly due to the unique vegetation types found in desert shrublands, which mainly consist of prostrate shrubs and short-stature woody trees, there are no published studies of PyC production in these ecosystems. Therefore, we simply applied a global temperate grassland PyC/CO_2 ratio to estimate the PyC production in these regions. Similarly, the tundra regions have no available quantitative information on PyC production or conversion rates, although the presence of charcoal in tundra soils can be abundant (e.g., Qi et al., 2017). Recent climatic warming has caused pronounced environmental changes, including shrub expansion and vegetation type change in the tundra region (Myers-Smith et al., 2011), but the paucity of available information on PyC limits our ability to assess the impact of these changes on PyC

production. Therefore, as with desert ecosystems, we simply employed the same PyC/CO_2 ratio for temperate grassland to calculate the PyC production in tundra areas.

2.2.7. Conversion Ratio Estimation

In this study, we used a Monte Carlo approach to obtain the PyC/CO_2 conversion ratio for each biome region, as follows. First, for each biome region, five conversion ratios from published studies were randomly selected (boreal forest had four; see below). If there were insufficient studies for a given region, conversion ratios from a similar biome were selected to construct the estimate. If the published conversion ratio appeared as a range, a number within this range (to one decimal or 0.1%) was randomly generated. For example, the conversion ratio 5.0–7.0% was used to generate a list of ratios: 5.0% 5.1%, 5.2%, …, 7.0%; a ratio was then randomly selected from this list. Second, one conversion ratio was calculated as the mean of the five selected ratios (boreal forest had four). Third, this process was repeated 100 times to produce a set of conversion ratios, from which means and standard deviations were calculated.

Selecting five PyC/CO_2 conversion ratios for each biome presented a challenge, given the dearth of published studies from several biomes (Table 1). For the boreal forest biome, all four ratios obtained from the literature were used here. For temperate forest in North and South America, the five published ratios in the United States were used. For temperate forest in Australia, the conversion ratios for Australian and global temperate forest with two randomly selected ratios from the other six temperate forest studies were used. For temperate forest in Eurasia, conversion ratios for Germany and global studies were selected with three randomly selected ratios from the other seven studies. For tropical forest, all nine ratios were used. For temperate grassland in Eurasia, the published ratios in Asia and the United Kingdom were used with other two randomly selected from the three global studies. For temperate grassland in North and South America, the published ratio in America was used with other four randomly selected ratios. For tropical savanna in Africa, four conversion ratios randomly selected from five African studies with one global ratio were used. For tropical savanna in Australia, four studies in Australia and one from the other six studies were used. For desert, xeric shrubland and tundra, five randomly selected ratios for temperate grassland were used.

3. Results

3.1. PyC Conversion Ratio

Through these Monte Carlo estimates, overall, the highest PyC conversion ratio was in boreal forest, having a value of 11.7 ± 0.2 (Figure 2). In temperate forest regions, North and South America had the lowest ratio of 6.9% ± 0.5%, and Australia had a similar ratio of 7.1% ± 0.8%, but Eurasia had the highest ratio of 7.4% ± 1.0%. In tropical forest, the ratio was 7.8% ± 1.3%. Globally, the lowest PyC conversion ratio was in Eurasian temperate grassland, having a value of 2.9% ± 0.4%, while the ratio increased to 3.1% ± 0.4% in North and South American temperate grassland. African tropical savanna had a value of 7.8% ± 0.9%, while it decreased to 7.2% ± 1.0% in tropical savanna of Australia. The PyC conversion ratio in desert, xeric shrubland and tundra, was 3.1% ± 0.5%.

3.2. CO_2 Emissions

The CO_2 emissions from GFED4s had been reported by van der Werf et al. (2017) and summarized here according to the biome and continent regions used in this study. Over the 2000–2010 study period, GFED4s estimated that on average, 2,086 Tg C/year was released to the atmosphere as direct CO_2 emissions from global fires (Table 2), with a minimum in 2009 (1,838 Tg C) and a maximum in 2002 (2,314 Tg C). By comparison, TEM6 estimated direct CO_2 emissions from global fires as an average of 643 Tg C/year over the same time period, with a minimum in 2010 (492 Tg C) and maximum in 2003 (898 Tg C). The GFED4s results suggested that fires in African ecosystems were responsible for more than half (1,126 Tg C/year) of the global fire-related CO_2 emissions, and 90% (1,010 Tg C/year) of this estimate was contributed by savanna fires. In contrast, TEM6 results suggested that fires in Eurasian ecosystems were responsible for approximately 50% (310 Tg C/year) of its estimated global total. GFED4s results indicate that North American ecosystems produced the least amount of CO_2 from fires (82 Tg C/year) during the 2000 to 2010 time period, while TEM6 results identify the least amount from Australian ecosystems (10 Tg C/year). At the global scale, results from both models suggested that grassland fires (including temperate grassland and tropical savanna) emitted the largest amount of CO_2 (1,258 Tg C/year from GFED4s and 187 Tg C/year from TEM6; Table 3). In tropical forest

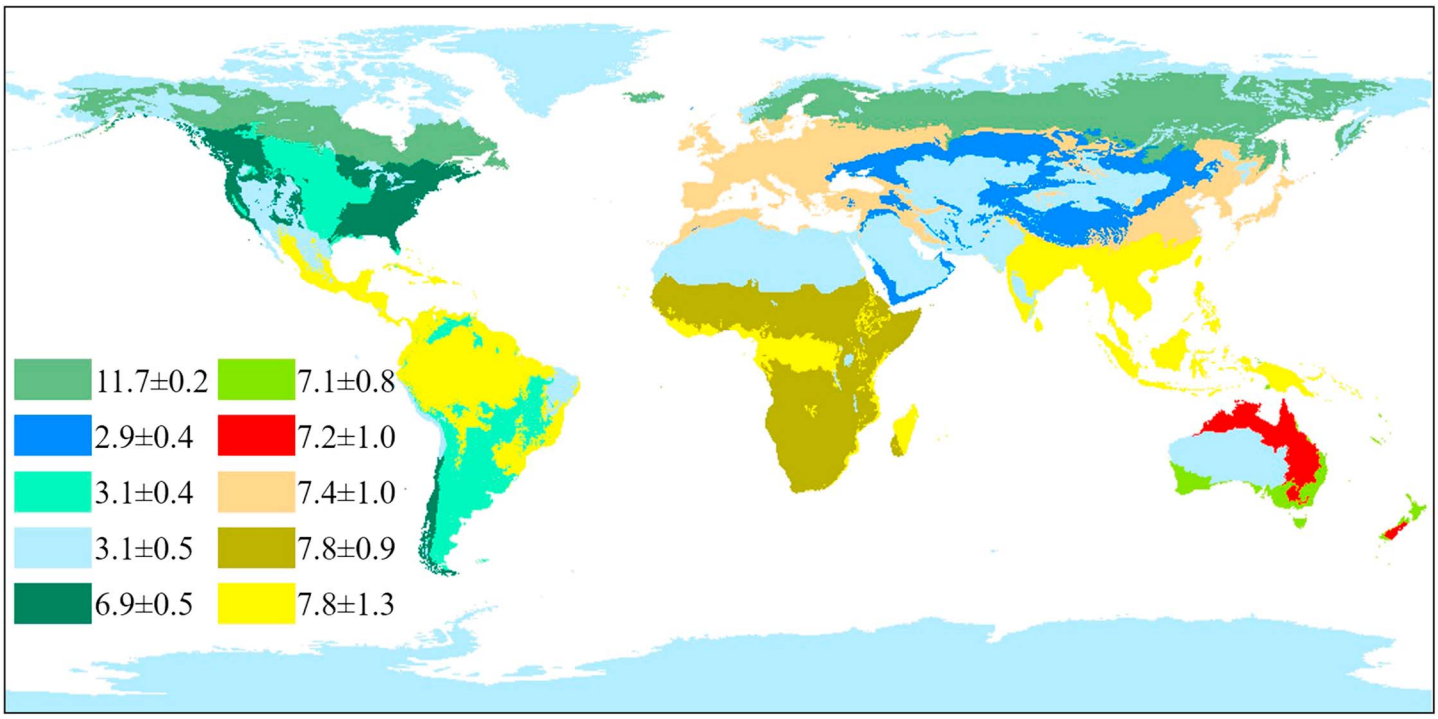

Figure 2. The spatial distribution of pyrogenic carbon conversion ratios by biome.

regions, GFED4s estimated CO_2 emissions from fires to be 569 Tg C/year, compared to 172 Tg C/year estimated by TEM6. GFED4s estimated a 102-Tg C/year release of CO_2 from fires across global temperate forest regions during this time period, which was larger than the TEM6 estimate (73 Tg C/year). Although their estimates differ among the four temperate forest regions, both models identify the Eurasian temperate forest as producing the greatest amount of CO_2 (52 and 61 Tg C/year), while the South American temperate forest released the least amount (2 and 1 Tg C/year). In addition, GFED4s results suggested that CO_2 amounts released from global desert and tundra fires were 34 and 15 Tg C/year, respectively, and both are similar to the TEM6 estimates (34 and 21 Tg C/year).

During the period 2000–2016, the global fire CO_2 emissions estimated from GFED4s results was 2,041 Tg C/year. While TEM6 results were only available up to 2010, we analyzed the GFED4s results from 2011 to 2016, which estimated direct CO_2 emissions during this time period to be 1,959 Tg C/year globally as a result of fires. During this later time period, African land ecosystems again produced the greatest amount of CO_2, responsible for more than 50% of the global emissions. Compared to that in the 2000–2010 time period, CO_2 released from South American tropical forest decreased by 33% (73 Tg C/year), having the largest absolute reduction of all biomes. CO_2 released from the North American boreal forest increased by 76% (31 Tg C/year), having the largest percentage increase. CO_2 released from tropical savannas decreased by 6% (68 Tg C/year), having the minimum rate of change.

3.3. PyC Production

During the 2000–2010 analysis period, the average global PyC production from fires was 153.0 ± 19.3 Tg C/year, as estimated from the GFED4s results (PyC_{GFED4s}), ranging from 139.6 ± 16.4 Tg C in 2008 to 173.5 ± 20.6 Tg C in 2002 (Table 2). In comparison, the average global PyC production from fires as estimated from the TEM6 results (PyC_{TEM6}) was 49.5 ± 4.9 Tg C/year, ranging from 37.1 ± 4.1 Tg C (2010) to 73.1 ± 5.6 Tg C (2003). PyC_{GFED4s} suggested the largest amount of PyC (58.3% ± 6.2% of total) was produced in African land ecosystems, while PyC_{TEM6} suggested 22.3% ± 2.4% was produced there. (Note that the percent difference between two distributions was estimated by a Monte Carlo approach. Initially, 100 paired samples, that is, one from each distribution, were randomly selected from the two distributions, and the percent difference for each pair was calculated. Finally, mean and standard deviation were obtained from the

Table 2
Modeled Estimates of the Average Annual CO_2 Emissions and PyC Production (Tg C/year)

	GFED4s				TEM6	
	2000–2010		2011–2016		2000–2010	
Region/Biome	CO_2	PyC	CO_2	PyC	CO_2	PyC
Africa	1,125.8	87.8 ± 10.6	1,051.2	82.0 ± 9.9	141.0	11.0 ± 1.4
Tropical forest	115.7	9.0 ± 1.5	111.0	8.7 ± 1.4	37.4	2.9 ± 0.5
Tropical savanna	1010.0	78.8 ± 9.1	940.0	73.3 ± 8.5	103.6	8.1 ± 0.9
Desert, xeric shrubland	0.1	0.0 ± 0.0	0.2	0.0 ± 0.0	0.0	0.0 ± 0.0
Australia	124.6	8.3 ± 1.1	128.0	8.3 ± 1.1	10.4	0.8 ± 0.1
Temperate forest	30.2	2.2 ± 0.2	26.2	1.9 ± 0.2	6.5	0.5 ± 0.1
Tropical savanna	77.4	5.6 ± 0.8	79.5	5.7 ± 0.8	3.8	0.3 ± 0.0
Desert, xeric shrubland	16.9	0.5 ± 0.1	22.2	0.7 ± 0.1	0.0	0.0 ± 0.0
Eurasia	388.4	30.0 ± 3.7	402.6	32.8 ± 3.8	309.8	24.5 ± 1.7
Boreal forest	67.2	7.9 ± 0.1	93.0	10.9 ± 0.2	128.9	15.1 ± 0.3
Temperate forest	52.4	3.9 ± 0.5	41.0	3.0 ± 0.4	60.7	4.5 ± 0.6
Tropical forest	213.3	16.6 ± 2.8	228.2	17.8 ± 3.0	27.7	2.2 ± 0.4
Temperate grassland	42.0	1.2 ± 0.2	29.2	0.8 ± 0.1	60.0	1.7 ± 0.2
Desert, xeric shrubland	13.5	0.4 ± 0.1	11.2	0.3 ± 0.1	32.5	1.0 ± 0.2
North America	81.6	7.5 ± 0.4	114.3	11.2 ± 0.4	36.9	3.7 ± 0.1
Boreal forest	40.6	4.8 ± 0.1	71.5	8.4 ± 0.1	28.2	3.3 ± 0.1
Temperate forest	17.8	1.2 ± 0.1	20.9	1.4 ± 0.1	4.6	0.3 ± 0.0
Tropical forest	18.5	1.4 ± 0.2	17.1	1.3 ± 0.2	1.7	0.1 ± 0.0
Temperate grassland	3.7	0.1 ± 0.0	3.5	0.1 ± 0.0	1.1	0.0 ± 0.0
Desert, xeric shrubland	1.0	0.0 ± 0.0	1.3	0.0 ± 0.0	1.3	0.0 ± 0.0
South America	350.4	19.0 ± 3.4	251.4	15.0 ± 2.3	124.5	8.9 ± 1.5
Temperate forest	1.5	0.1 ± 0.0	2.2	0.2 ± 0.0	0.9	0.1 ± 0.0
Tropical forest	221.4	17.3 ± 2.9	148.3	11.6 ± 1.9	105.0	8.2 ± 1.4
Temperate grassland	124.9	3.9 ± 0.5	98.7	3.1 ± 0.4	18.4	0.6 ± 0.1
Desert, xeric shrubland	2.7	0.1 ± 0.0	2.1	0.1 ± 0.0	0.2	0.0 ± 0.0
Tundra	15.0	0.5 ± 0.1	11.0	0.3 ± 0.1	20.7	0.6 ± 0.1
Total	2,085.7	153.0 ± 19.3	1,958.5	149.6 ± 17.7	643.3	49.5 ± 4.9

Note. Shaded rows indicate sums. PyC = pyrogenic carbon; GFED4s = Global Fire Emissions Database version 4; TEM6 = Terrestrial Ecosystem Model version 6.

100 percentages.) PyC_{TEM6} suggested the largest amount of PyC (50.2% ± 4.2% of total) was produced in Eurasian land ecosystems, while PyC_{GFED4s} suggested 19.0% ± 2.1% was produced there. PyC_{GFED4s} suggested that North American land ecosystems produced the least amount at 37.5 ± 0.4 Tg C/year, but PyC_{TEM6} suggested Australian land ecosystems produced the least amount at 0.8 ± 0.1 Tg C/year.

Table 3
Modeled Estimates of the CO_2 and PyC Produced From Fires and Summarized at the Global Biome Scale (Tg C/year)

	GFED4s				TEM6	
	2000–2010		2011–2016		2000–2010	
Biome	CO_2	PyC	CO_2	PyC	CO_2	PyC
Boreal forest	107.8	12.7 ± 0.2	164.4	19.2 ± 0.3	157.0	18.4 ± 0.4
Temperate forest	101.9	7.4 ± 0.8	90.4	6.5 ± 0.7	72.7	5.3 ± 0.7
Tropical forest	568.8	42.7 ± 7.4	504.6	39.4 ± 6.6	171.9	13.4 ± 2.2
Temperate grassland	170.6	4.4 ± 0.7	131.4	4.0 ± 0.5	79.5	2.3 ± 0.3
Tropical savanna	1,087.4	84.4 ± 9.9	1,019.6	79.1 ± 9.3	107.4	8.4 ± 1.0
Desert, xeric shrubland	34.2	1.0 ± 0.2	37.1	1.1 ± 0.2	34.1	1.1 ± 0.2
Tundra	15.0	0.4 ± 0.1	11.0	0.3 ± 0.1	20.7	0.6 ± 0.1
Total	2,085.7	153.0 ± 19.3	1,958.5	149.6 ± 17.7	643.3	49.5 ± 4.9

PyC_{GFED4s} suggested that tropical savanna fires created the greatest amount at 84.4 ± 9.9 Tg C/year, while PyC_{TEM6} suggested that boreal forest fires created the greatest amount at 18.4 ± 0.4 Tg C/year (Table 3). PyC_{GFED4s} suggested that 28.1% ± 4.0% (42.7 ± 7.4 Tg C/year) of the global PyC total was produced in tropical forests, while PyC_{TEM6} suggested 28.2% ± 3.4% (13.4 ± 2.2 Tg C/year) was produced there. In temperate forest ecosystems, PyC_{GFED4s} estimated the PyC production at 7.4 ± 0.8 Tg C/year, which was higher than PyC_{TEM6} estimate (5.3 ± 0.7 Tg C/year). However, in boreal forest ecosystems, PyC_{GFED4s} estimated the PyC production at 12.7 ± 0.2 Tg C/year, which was lower than PyC_{TEM6} estimate (18.4 ± 0.4 Tg C/year). In desert and tundra regions, PyC_{GFED4s} estimated 1.0 ± 0.2 and 0.4 ± 0.1 Tg C/year, respectively, of PyC formed through fires, which are very close to estimates from PyC_{TEM6} (1.1 ± 0.2 and 0.6 ± 0.1 Tg C/year, respectively).

During the period 2000–2016, global PyC production was estimated as 153.4 ± 18.7 Tg C/year based on the GFED4s results. Because TEM6 results were only available up to 2010, we analyzed the PyC results from GFED4s during the period 2011–2016, which indicated an average of 149.6 ± 17.7 Tg C/year PyC produced by fires. Fires in African ecosystems still produced the greatest amount of PyC (82.0 ± 9.9 Tg C/year), and 89.3% ± 8.0% resulted from African savanna burning. Compared with that in the period 2000–2010, PyC produced from African tropical savanna decreased by 7.4% ± 6.5% (5.5 ± 3.6 Tg C/year), having the largest absolute reduction. PyC produced from North American boreal forest increased by 77.0% ± 2.2% (3.56 ± 0.2 Tg C/year), having the largest percentage increase. PyC produced from South American tropical forest decreased by 26.4% ± 4.5% (4.15 ± 1.7 Tg C/year), having the largest percentage reduction.

4. Discussion

We improved current PyC estimations (e.g., Bird et al., 2015; Kuhlbusch & Crutzen, 1995; Santín et al., 2016) in three aspects. First, we used estimates of fire-induced CO_2 emissions from two ecosystem models (GFED4s and TEM6), along with published biome-specific PyC/CO_2 ratios, to estimate the PyC production. To the best of our knowledge, ours is the first attempt to estimate PyC production from fires at a global scale, based on detailed biome-specific PyC production rates.

Second, we depicted the spatial distributions and dynamics of global fire-produced CO_2 and PyC, which made it possible to compare PyC production in biome and continental scales. GFED4s identified Africa as the largest source of fire-produced CO_2 (Figure 3a); in contrast, TEM6 identified Eurasia as the largest source (Figure 3b). GFED4s suggested that African tropical savanna fires released the largest amount of CO_2; however, TEM6 suggested that Eurasian boreal forest released the largest amount. Using the detailed biome-specific PyC conversion ratios with the two modeling results, both PyC_{GFED4s} and PyC_{TEM6} suggested that African savanna fires produced the largest amount of PyC (Figures 4a and 4b).

Third, our results provided the interannual variations of fire-produced CO_2 emissions and PyC production. They varied among continental regions and among biomes. Both GFED4s and TEM6 indicated that this variation was greatest in tropical forests. Interannual variation of CO_2 emissions and PyC production among other biomes was markedly lower. The higher interannual variability in the tropics may be attributable to ever-changing patterns in slash-and-burn agriculture (van Marle et al., 2017), leading to varying CO_2 emissions and PyC production. Extreme weather (e.g., drought or El Niño) may be another contributor to this significant interannual variability (Chen et al., 2017). Alencar et al. (2006) reported that El Niño can significantly increase the annual fire frequency and burning area in Amazon tropical forest. Sloan et al. (2017) concluded that droughts induced by El Niño can magnify the frequency and severity of fire activity in South Asia.

PyC production from fires may represent approximately 0.2–0.6% of annual global net primary production (Huston & Wolverton, 2009). Though this percentage is relatively small, we emphasize that PyC is more recalcitrant than original biomass (Bird et al., 2017), meaning that it accumulates in terrestrial and marine ecosystems. Using the central reburning loss rate 7.8% and decomposition rate 0.5% of PyC (Landry & Matthews, 2017) over the study period, PyC_{GFED4s} suggested that a total of 1,415 ± 171 Tg C of PyC accumulated during the period 2000–2016 (Figure 5a), while PyC_{TEM6} suggested that 354 ± 35 Tg C accumulated during the period 2000–2010 (Figure 5b). These estimates suggested that PyC from fires may be a significant sink of atmospheric CO_2 when considered over longer time periods, assuming the postfire carbon can recover to the prefire status.

The CO_2 emitted and PyC produced by global fires were first discussed by Seiler and Crutzen (1980). They estimated the total amount of global biomass affected by fires using data on fuel burning efficiency

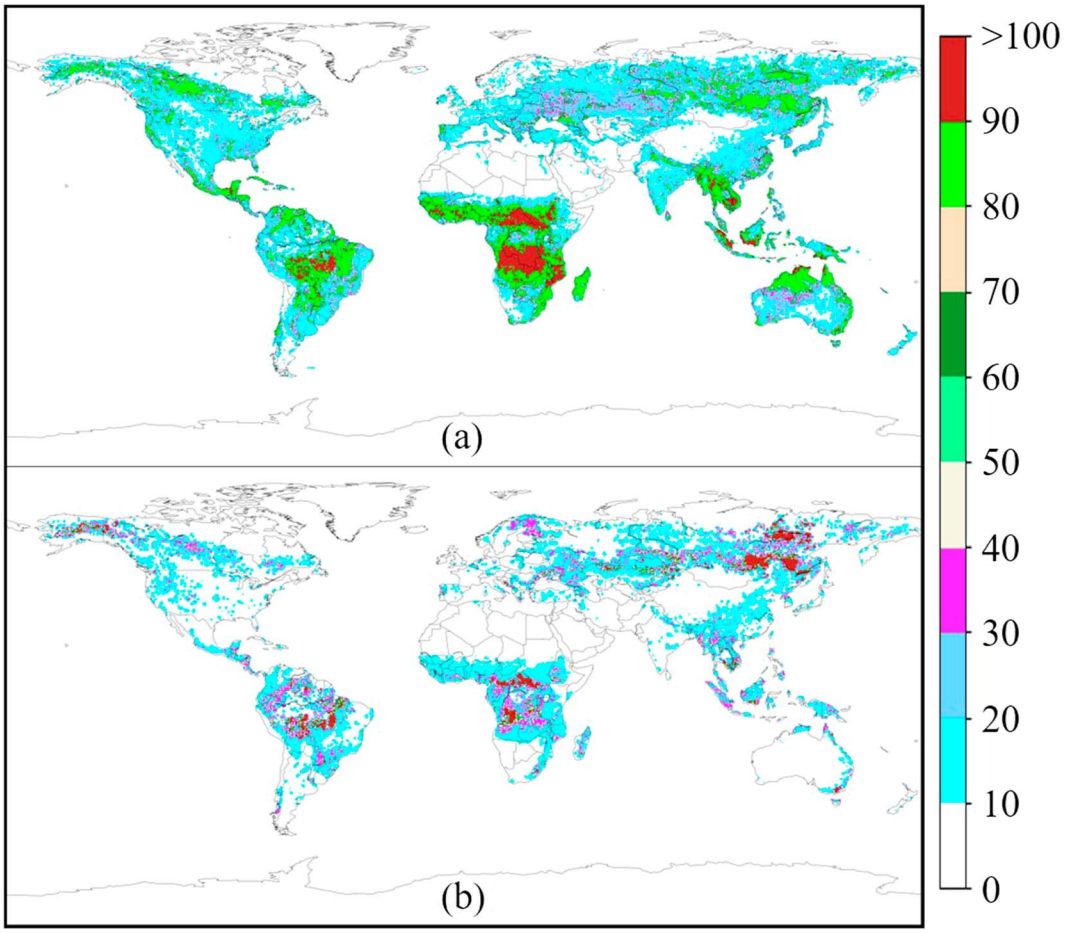

Figure 3. The mean of grid-weighted average annual CO_2 (g C·m^{-2}·year^{-1}) released from fires resulting from (a) GFED4s in the period of 2000–2016, and (b) TEM6 in the period of 2000–2010. GFED4s = Global Fire Emissions Database version 4; TEM6 = Terrestrial Ecosystem Model version 6.

along with global transfer rates of CO_2 and PyC in natural and agricultural ecosystems. They estimated global PyC production from biomass burning ranged from 500 to 1,700 Tg C/year, and CO_2 emissions from 2,000 to 4,000 Tg C/year. Crutzen and Andreae (1990) later estimated that global PyC production from fires ranged from 200 to 600 Tg C/year and CO_2 emissions from 2,700 to 6,800 Tg C/year. However, challenges in measuring PyC conversion rates and CO_2 emissions in diverse land ecosystems result in high uncertainties around these estimates (Crutzen & Andreae, 1990). Kuhlbusch and Crutzen (1995) attempted to reduce these uncertainties by measuring PyC in the residue after fires in laboratory-based measurements and clarified the relationships between PyC production and gaseous emissions. Using these refinements, they estimated global PyC production to be approximately 50 to 270 Tg C/year. Kuhlbusch and Crutzen (1996) then synthesized previous PyC conversion ratios across coarsely defined biome regions and concluded that global PyC production ranged from 50 to 200 Tg C/year. However, none of these estimates were conducted for specific time periods or provided PyC spatiotemporal dynamics. Bird et al. (2015) synthesized current knowledge of PyC production, stocks, and fluxes and estimated a production of 56–123 Tg C/year as char. Santín et al. (2016) used a global PyC conversion ratio with the GFED4s for the 1997–2014 time period to estimate that average annual PyC production ranged from 114 to 383 Tg C globally. In our study, the global CO_2 emitted annually from fires was estimated to be 2,041 Tg C/year during the period 2000–2016 obtained from GFED4s and 643 Tg C/year from TEM6 during 2000–2010. The corresponding global PyC production estimated from the GFED4s results was 153 ± 12 Tg C/year, and 50 ± 5 Tg C/year by TEM6, which roughly correspond with estimates of Bird et al. (2015).

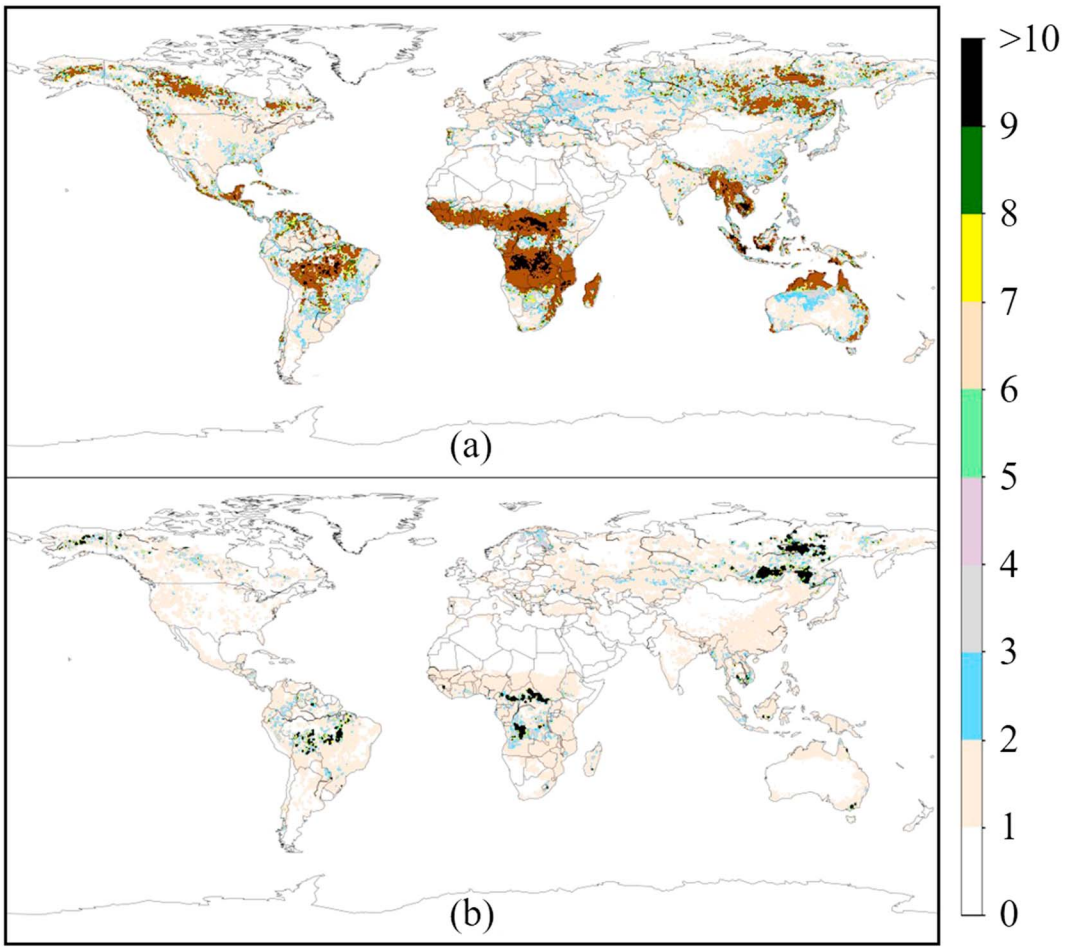

Figure 4. The mean of grid-weighted average annual PyC (g C·m^{-2}·year^{-1}) produced by fires, which were calculated from CO_2 emissions estimated by (a) GFED4s in the period of 2000–2016 and (b) TEM6 in the period 2000–2010. PyC = pyrogenic carbon; GFED4s = Global Fire Emissions Database version 4; TEM6 = Terrestrial Ecosystem Model version 6.

Our study revealed large differences between GFED4s and TEM6 results at both the biome level and the continental scale. In many cases, the two models produced quite different estimates of both CO_2 and thus PyC production. They often differed in the relative ranking of continental regions and biomes with respect to CO_2 and PyC production. Both models use similar area burned data from satellite image sources, but, unlike GFED4s, TEM6 does not incorporate small fires or agricultural burning in its estimates. When the small fires are excluded, GFED4 estimates 1,500 Tg C/year of CO_2 emissions in the period 1997–2016 (van der Werf et al., 2017). The greatest difference between the two model estimates was in the tropical savanna biome, which was responsible for 69.4% ± 4.5% of the total difference. The second was the tropical forest biome consisting of 27.9% ± 2.9% of the total difference. These uncertainties could arise from the input data, simulated biochemical processes, and model parameters. In addition, these differences in estimates of the carbon impacts of fire between the two modeling approaches are a function of how each simulates the carbon pools that are exposed to fire and the fire severity parameters that transfer carbon among them. Therefore, future improvement for the input data (e.g., burn area, burn severity, climate data, fuel load, and vegetation map), simulated biochemical processes (e.g., photosynthesis, respiration, and biomass decomposition), and related parameters (e.g., combustion completeness, combustion efficiency, and emission factors) can enhance their estimation abilities.

In this study, we used conversion ratios from simulated distributions (constrained by published ratios) to estimate annual global PyC production from fires. Because weather conditions, fuel loads, fuel types, and fire types influence these PyC conversion ratios, their use contributes to the uncertainties in our results. Given

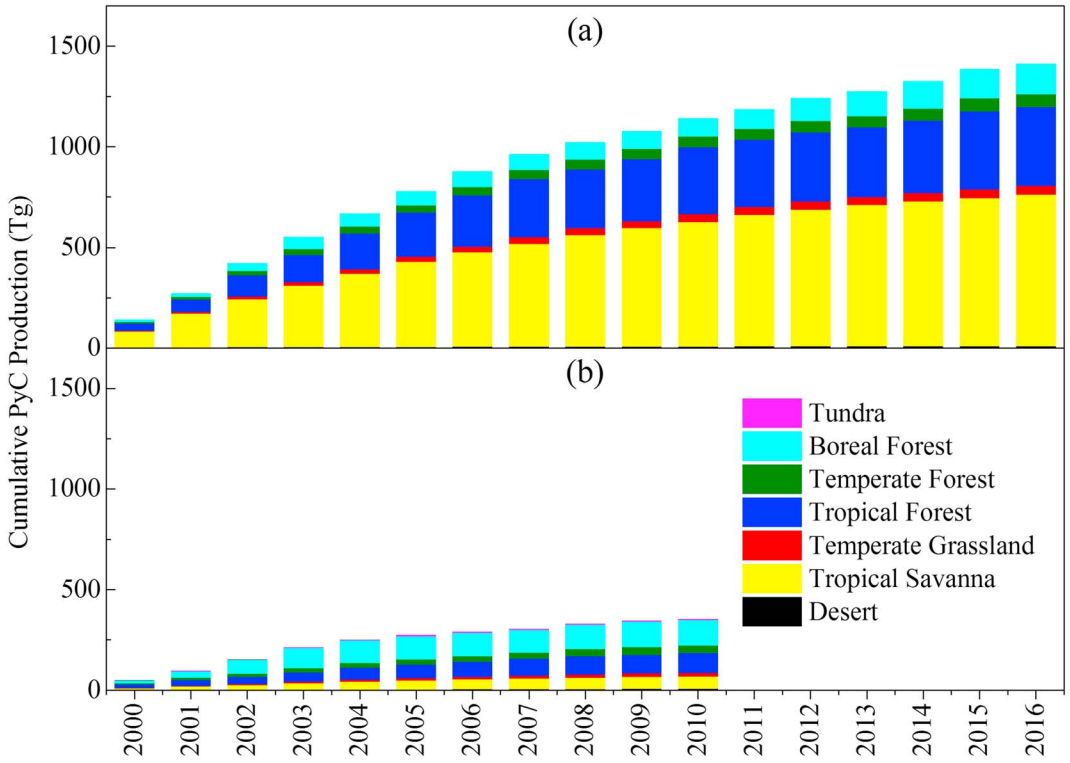

Figure 5. The mean of cumulative PyC production estimated from CO_2 emissions provided by (a) GFED4s from 2000 to 2016 and (b) TEM6 from 2000 to 2010. PyC = pyrogenic carbon; GFED4s = Global Fire Emissions Database version 4; TEM6 = Terrestrial Ecosystem Model version 6.

the factors that influence the PyC production, our estimate could be improved in at least three regards. First, Kuhlbusch and Crutzen (1995) summarized the PyC/CO_2 conversion ratios in various fire types (e.g., wildfire, prescribed fire, and deforestation fire) and concluded that fire types could influence the conversion ratio. Miesel et al. (2018) reported that intense fire type (e.g., prescribed fire) could significantly increase PyC production, thereby increasing the PyC/CO_2 conversion ratio. Thus, the lack of fire type information can underestimate the PyC production. Although we employed a sensitivity test with published conversion ratios, detailed fire type information along with corresponding released carbon could decrease the fire type uncertainties in PyC estimates.

Second, the paucity of fuel type information in various biomes precludes further refinements in our calculations. Using before-versus-after fire inventories, Tinker and Knight (2000) concluded that the presence of coarse fuel biomass can increase PyC production. Similarly, Ward et al. (2017) found that coarse fuel biomass significantly increased PyC production during burning. However, in our study, the influence of coarse fuel loads on PyC production was not considered, which may have led to underestimates of PyC production; the magnitude of this underestimate is unknown. Therefore, fuel type and fuel load information could improve the calibration of PyC conversion ratios, thereby improving estimates.

Third, although we employed biome- and continental-scale PyC conversion ratios to improve existing the PyC estimates, agricultural fire was not considered as one special class. Thus, improved PyC estimates for agricultural fire would decrease the uncertainties in our estimates. Seiler and Crutzen (1980) reported agricultural fire had a different PyC conversion ratio from that of its biome (the PyC/CO_2 was not presented in their study), and agricultural fire produced 53% of the total burned carbon. Through summarizing published studies, Kuhlbusch and Crutzen (1995) also reported that the PyC conversion ratio for agricultural fire differed from that of its biome.

Though unrelated to our modeling approach, we note that authors have chosen different fuel types (see Table 1, e.g., forest floor, slash pile, and woody debris), carried out the burning in different fire conditions

(e.g., experimental, laboratory, and wildfire), and used various size criteria to define PyC types (size of visual charcoal are defined differently in various studies). All of these differences presumably influence PyC conversion ratios. Future modeling approaches aimed at global carbon accounting could benefit from a standardized measurement for PyC in order to increase predictive confidence of such models.

5. Conclusions

Our approach—based on biome-specific PyC/CO_2 ratios—represents an improved estimate of global PyC emissions from fires. These fires represent a large carbon source to the atmosphere by releasing CO_2 and other gaseous carbon compounds; however, they also create PyC in the form of charred material that remains on site or small particles that are transported far from the site of origin (Bird et al., 2015; Cotrufo et al., 2016). Because PyC is more recalcitrant to decay than original biomass, the accumulated PyC may serve as a potentially growing, stable carbon sink that is distributed globally. We believe the size of this carbon pool and the processes responsible for its formation merit further research attention.

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