Biomass burning fuel consumption rates: A field measurement database

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Abstract

Landscape fires show large variability in the amount of biomass or fuel consumed per unit area burned. Fuel consumption (FC) depends on the biomass available to burn and the fraction of the biomass that is actually combusted, and can be combined with estimates of area burned to assess emissions. While burned area can be detected from space and estimates are becoming more reliable due to improved algorithms and sensors, FC is usually modeled or taken selectively from the literature. We compiled the peer-reviewed literature on FC for various biomes and fuel categories to better understand FC and its variability, and to provide a database that can be used to constrain biogeochemical models with fire modules. We compiled in total 77 studies covering 11 biomes including savanna (15 studies, average FC of 4.6 t DM (dry matter) ha^{-1} with a standard deviation of 2.2), tropical forest (n=19, FC=126±77), temperate forest (n=12, FC=58±72), boreal forest (n=16, FC=35±24), pasture (n=4, FC=28±9.3), shifting cultivation (n=2, FC=23, with a range of 4.0 - 43), crop residue (n=4, FC=6.5±9.0), chaparral (n=3, FC=27±19), tropical peatland (n=4, FC=314±196), boreal peatland (n=2, FC=42 [42-43]), and tundra (n=1, FC=40). Within biomes the regional variability in the number of measurements was sometimes large, with e.g. only 3 measurement locations in boreal Russia and 35 sites in North America. Substantial regional differences in FC were found within the defined biomes: for example FC of temperate pine forests in the USA was 37% lower than Australian forests dominated by eucalypt trees. Besides showing the differences between biomes, FC estimates were also grouped into different fuel classes. Our results highlight the large variability in FC, not only between biomes but also within biomes and fuel classes. This implies that substantial uncertainties are associated with using biome-averaged values to represent FC for whole biomes. Comparing the compiled FC values with co-located Global Fire Emissions Database version 3 (GFED3) FC indicates that modeling studies that aim to represent variability in FC also within biomes still require improvements as they have difficulty in representing the dynamics governing FC.

1. Introduction

Landscape fires occur worldwide in all biomes except deserts, with frequencies depending mostly on type of vegetation, climate, and human activities (Crutzen, 1990; Cooke and Wilson, 1996; Andreae and Merlet, 2001; Bowman et al., 2009). The amount of fire-related research is increasing, partly due to improved abilities to monitor fires around the world using satellite data and appreciation of the important role of fires in the climate system and for air quality (Bowman et al., 2009, Johnston et al., 2012). Studies focusing on the effects of fires on the atmosphere require accurate trace gas and particle emission estimates. Historically, these are based on the Seiler and Crutzen (1980) equation, multiplying burned area, fuel loads (abbreviated as 'FL' in the remainder of the paper), combustion completeness (abbreviated as 'CC' in the remainder of the paper), and emission factors over time and space of interest. These four properties are obtained in different ways and generally uncertainties are substantial (van der Werf et al., 2010). The burned area may be estimated directly from satellite observations, with the MODerate resolution Imaging Spectroradiometer (MODIS) 500 m maps (Roy et al., 2005; Giglio et al., 2009) being currently the most commonly used products for large-scale assessments. Although small fires and fires obscured by forest canopies escape detection with this method (Randerson et al. 2012), the extent of most larger fires can be relatively well constrained in this way. With burned area estimates improving the other parameters may become the most uncertain component when estimating emissions (French et al., 2004) as they are less easily observed from space. In general, the FL is equivalent to the total biomass available. New studies do provide estimates of standing biomass (e.g. Baccini et al., 2012). However, fires do not necessarily affect standing biomass. Especially in savannas the trees are usually protected from burning by a thick barch and in some of the literature the FL therefore has a more restrictive definition, referring to only that portion of the total available biomass that normally burns under specified fire conditions, which is often only the fine ground fuels. In both definitions the FL is typically expressed as the mass of fuel per unit area on a dry weight basis. CC corresponds to the fraction of fuel exposed to a fire that was actually consumed or volatilized. Just like total FL, CC cannot be directly derived from satellite observations. Instead, these quantities are usually based on look-up tables of biome-average values, or calculated from global vegetation models including Dynamic

Global Vegetation Models (DGVM, e.g. Kloster et al., 2010) and biogeochemical models (e.g. Hély et al., 2007; van der Werf et al., 2010).

Another approach that has been developed over the past decade is the measurement of fire radiative power (FRP) (Wooster et al., 2003; Wooster et al., 2005; Kaiser et al., 2012). FRP per unit area relates directly to the fuel consumption (abbreviated as 'FC' in the remainder of the paper) rate, which again is proportional to the fire emissions. The FRP method has several advantages compared to the Seiler and Crutzen (1980) approach, such as the ability to detect smaller fires and the fact that the fire emissions estimates derived this way do not rely on FL or CC. One disadvantage is that the presence of clouds and smoke can prevent the detection of a fire, and the poor temporal resolution of polar orbiting satellites hampers the detection of fast moving or short-lived fires (which still can show a burn scar in the burned area method) and makes the conversion of FRP to fire radiative energy (FRE, time-integrated FRP) difficult.

Finally, emission factors, relating the consumption of dry matter to trace gas and aerosol emissions of interest, are obtained by averaging field measurements for the different biomes. Andreae and Merlet (2001) have compiled these measurements into a database that is updated annually, while Akagi et al. (2011) used a similar approach to derive biome-averaged emission factors, but focused on measurement of fresh plumes only and provided more biome-specific information. The accompanying database is updated frequently and on-line.

To improve and validate fire emissions models, it is crucial to gain a better overview of available FC measurements, as well as of the FL and CC components that together govern FC. This is obviously the case for emissions estimates based on burned area, but also FRP-estimates could benefit from this information because one way to constrain these estimates is dividing the fire-integrated FRE by the fire-integrated burned area, which in principle should equal FC.

Over the last decades, many field measurements of FL and CC have been made over a range of biomes and geographical locations. An examination of these studies revealed several generalities: Forested ecosystems in general show relatively little variability in FL over time for a given location, but CC can vary due to weather conditions. Fine fuels usually burn more complete than coarser fuels, and therefore CC in grassland savannas is often higher than in forested ecosystems. While CC in the savanna biome shows relatively little variability over time, the FL can vary on monthly time scales depending on season, time since fire, and grazing rates. Another generalization that can be made is that FL in boreal and tropical forests are relatively similar, but the distribution into components (organic soil, boles, peat) is very different with FL in tropical forests being mostly composed of aboveground biomass while in the boreal region the organic soil (including fermentation and humus layers) represents a large part of the FL. Overall CC is often higher in tropical forests though, leading to higher FC values.

While these findings are relatively easy to extract from the body of literature, what is lacking is a universal database listing all the available measurements so that they can be compared in a systematic way, used to constrain models, and to identify gaps in our knowledge with regard to spatial representativeness. Building on Akagi et al. (2011), who listed 47 measurements for nine fuel types, this paper is a first attempt to establish a complete database, listing all the available FC field measurements for the different biomes that were found in the peer-reviewed literature. We focus on FC estimates, but if FL and/or CC were reported separately these were included as well. The database, available at http://www.globalfiredata.org/FC, will be updated when new information becomes available. In follow-up papers we aim to provide more in-depth analyses on the variability we found; the goal of this paper is to give a quantitative overview of FC measurements made around the world to improve large-scale fire emission assessments. This paper is organized as follows: in Section 2 we list all the measurements and divide them into 11 different biomes. In that section we also provide a short summary of the methods used during the field campaigns, give a brief introduction about fire processes in each biome, and present data for different fuel classes (ground, surface, and crown fuels). Our findings are discussed in Section 3, and in addition a comparison between the FC field measurements and 1) the values used in GFED3 (van der Werf et al., 2010) modeling framework, and 2) several FRE-derived estimates, is given. Finally, our results are summarized in Section 4.

2. Measurements

Figure 1 provides an overview of the locations where peer-reviewed FC was measured in the field, overlaid on mean annual fire carbon (C) emissions (van der Werf et al., 2010). Field measurements of FC were conducted in most fire-prone regions in the world, including the 'arc of deforestation' in Amazonia, the boreal regions of North America, and savannas and woodlands in Africa, South America and Australia. Due to ecological, technical, and logistical reasons (e.g. wildfire versus prescribed fire), the FL and FC sampling procedures on these measurement locations have ranged in scope from simple and rapid visual assessment (e.g. Maxwell, 1976; Sandberg et al., 2001) to highly detailed measurements of complex fuel beds along lines (line transect method: van Wagner 1968) or in fixed areas (planar intersect method; Brown, 1971) that take considerable time and effort. Most of the studies we found in the literature rely on the planar intersect method (PIM), where fuel measurement plots are typically divided in multiple, randomized smaller subplots. The (small-size) biomass in these subplots is oven dried and weighed both pre- and post-fire to estimate the CC and to determine the FC. The consumption of larger-size material (diameter >10cm) is often estimated based on experimental observations of randomly selected trunks and branches that were identified before the fire (Araújo et al., 1999). The PIM is mainly applied in prescribed burns, and obtaining FC measurements for large wildfires is logistically more challenging but can be based on comparing burned with adjacent unburned patches. Usually, the total FC of a fire is presented, but some studies also include separate values for different fuel categories of the total belowground biomass (peat, organic soils, and roots) and total aboveground biomass (aboveground litter and live biomass). Diameters of woody fuels have been classified according to their 'time-lag', which refers to the length of time that a fuel element takes to respond to a new moisture content equilibrium (Bradshaw et al., 1983). The time lag categories traditionally used for fire behavior are specified as: 1hr, 10hr, 100hr, and 1000hr and correspond to round woody fuels in the size range of 0-0.635cm, 0.635-2.54cm, 2.54-7.62cm, and 7.62-20.32cm, respectively. In this study we used US fire management standards to classify fuels into three different categories: 1) Ground (all materials lying beneath the surface including organic soil, roots, rotten buried logs, and other woody fuels), 2) Surface (all materials lying on or immediately above the ground including needles or leaves, grass, small dead wood, downed logs, stumps, large limbs, low brush, and reproduction) and 3) Crown (aerial) fuel (all green and dead materials located in the upper forest canopy including tree branches and crowns, snags, moss, and high brush).

Although a substantial body of grey literature of FC measurements is available, we focused on peer-reviewed studies. An exception was made for a few reports that focus on measurements conducted in the boreal forest and chaparral biome, because these reports were extensive and cited in peer-reviewed literature. Because the available data from the peer-reviewed literature was obtained from a wide variety of sources spanning multiple decades, the reported FC data needed to be standardized. We converted all FC measurements to units of tons dry matter per hectare (t ha^{-1}), which is the most commonly used unit. A carbon to dry matter conversion factor of two was used to convert carbon FC values to dry matter FC values. We note though that this conversion factor is not always representative for all biomes. Especially in the boreal regions –having a relative large contribution of organic soil fuels– but also in other biomes, this factor is sometimes lower and therefore our approach may slightly overestimate FL and FC.

In Table 1 we present the FL, CC, and FC data compiled for 11 different biomes that are frequently used in global fire emission assessments (e.g. van der Werf et al., 2010; Wiedinmeyer et al., 2011; Kaiser et al., 2012; Randerson et al., 2012). Some studies provided data for specific fuel classes (e.g. ground fuels) only, while others estimated a total FC for both the below and aboveground biomass. The data presented in Table 1 focussed on FC. Additional studies on FL measurements exist and were not included here, but listed in a spreadsheet that is available online at http://www.globalfiredata.org/FC. These estimates were extensive mostly for southern Africa (e.g. Scholes et al., 2011) and Australia (e.g. Rossiter et al., 2003). Including these additional field measurements may change regional FL averages. More specific details on the measurements and different fuel categories for each biome are listed in sections 2.1 – 2.11.

2.1. Savanna

Savanna fires in the tropics can occur frequently, in some cases annually. Their FL consists mainly of surface fuels (like grass and litter from trees), and is influenced both by rainfall of the previous years and time since last fire (Gill and Allan, 2008). Traditionally (African) savannas are split into dry and wet forms (Menaut et al., 1995). This split occurs at a precipitation rate of about 900 mm $year^{-1}$. Most savanna fires burn due to human ignition, but it is believed that these systems are seldom ignition limited, and more often limited by available fuel (Archibald et al., 2010). Fire incidence generally increases after years of above average rainfall, especially in dry savannas with low population densities (van Wilgen et al., 2004; Russell-Smith et al., 2007). As these systems are generally fuel limited, grass production and consumption by herbivores are very important factors controlling the extent of area burned particularly in drier regions where rainfall can vary strongly between years (Menaut et al., 1991; Cheney and Sullivan, 1997; Russell-Smith et al. 2007). Grass production controls fire spread because low-biomass grasslands have less continuous fuel swards, and also because they burn at lower intensities which reduces the probability of spread. In wet savannas the grass production is poorly correlated with rainfall and much higher than in dry savannas (10 to 20 t ha^{-1} $year^{-1}$, Gignoux et al., 2006). This results in higher intensity fires, keeping the landscape relatively open. In Australia, the division into dry and wet savannas is less clear. Annual grass production is typically low (less than 3 t ha^{-1} $year^{-1}$), even for precipitation rates of 2000 mm $year^{-1}$. This difference is mostly due to the fact that Australia's native grasses are limited by nitrogen availability at high rainfalls, something African grasses such as *Andropogon gayanus* overcome through various mechanisms (Rossiter-Rachor et al., 2009).

Miombo woodlands in Africa are high-rainfall savannas where up to 40% of the fuel can be provided by litter from trees (Frost et al., 1996). A similar type of vegetation can be found in Brazil, mainly consisting of woodlands with a closed canopy of tall shrubs and scattered trees (Cerrado denso). We found several measurements conducted in Miombo woodlands, as well as field measurements in the Brazilian Cerrado denso. Moreover, one study was found for an Indian deciduous forest, which can be classified as wooded savanna and thus the savanna biome (Ratnam et al., 2011).

For calculating averages, we divided the savanna biome into grassland savanna and wooded savanna by using the fuel type description that was provided in each study. The savanna measurements presented in Table 1a were taken between 1990 and 2009, and represent 17 unique measurement locations (Figure 1) taken from 15 different studies. For all measurements conducted, we found an average FL of 7.6±6.5 t ha^{-1} and FC of 4.6±2.2 t ha^{-1}. The average of the CC values as presented in the different studies indicated a value of 71±26%, higher than the ratio derived from the average FL and FC (61%) above. This difference is because not all FC measurements reported FL. Within the savanna biome, regional differences were found (Figure 2): FL and FC for South American savannas, 8.2±1.6 and 6.0±2.4 t ha^{-1}, respectively, were nominally higher than the ones measured in the savannas of Australia (5.1±2.2 and 3.6±1.6 t ha^{-1}). Measurements conducted in Africa, contributing to roughly 40% of all measurements in the biome, showed the lowest FC (3.4±1.0 t ha^{-1}) of all regions. A larger number of measurements are required to conclusively say whether these differences are statistically significant. To show the difference between grassland savannas and wooded savannas, data of both types of savanna are also provided in Figure 2. For grassland savannas the average FL was relatively low (5.3±2.0 t ha^{-1}) and the CC high (81±16%), yielding an average FC of 4.3±2.2 t ha^{-1}. Wooded savannas, on the other hand, had a higher FL (11±9.1 t ha^{-1}) but lower CC (58±32%), and therefore the average FC of 5.1±2.2 t ha^{-1} was only slightly higher than the one found for grasslands.

In Table 2 these values are given for different fuel categories. For the savanna biome most of the fuels were classified as surface fuels (Table 2a). In general, fuels with a large surface area to volume ratio (like litter, grass and dicots) had a high CC of at least 88%. CC values were significantly lower for the woody debris classes, with a minimum of 21±12% found for woody fuels with a diameter larger than 2.54cm (100hr fuel). FC for the different fuel types was between 0.3 and 1.9 t ha^{-1}, with litter having the highest values. In general the total sum of different fuel categories agrees well with the biome-averaged values presented. However, not all measurements distinguished between fuel categories and therefore small discrepancies were sometimes found: for FC in the savanna biome, for example, the sum of different fuel categories is 5.3 t ha^{-1}, slightly higher than the biome average of 4.6±2.2 t ha^{-1}.

2.2. Tropical forest

Tropical evergreen forests are generally not susceptible to fire except during extreme drought periods (e.g. Field et al., 2009; Marengo et al., 2011; Tomasella et al., 2013) due to their dense canopy cover keeping humidity high and wind speed low, and also because the amount of fuel on the surface is low due to rapid decomposition. Human activities have resulted in fire activity in tropical forests, often with the goal to clear biomass and establish pasture or cropland. These deforestation fires can be small-scale (e.g. shifting cultivation, discussed in Section 2.6) or on large scale with the aid of heavy machinery. In the latter case, biomass is often piled in windrows after the first burn and subject to additional fires during the same dry season to remove the biomass more completely. In large-scale deforestation regions like the state of Mato Grosso in the Brazilian Amazon, the expansion of mechanized agriculture could result in increased fuel consumed per unit area (Cardille and Foley, 2003; Yokelson et al., 2007a). All these fires, but also selective logging, may lead to more frequent accidental fires as fragmented forests are more vulnerable to fire (Nepstad et al., 1999; Siegert et al., 2001; Pivello, 2011).

The total FL in tropical forests is mostly determined by the tree biomass (surface and canopy fuels) and generally on the order of a few hundred t ha^{-1}. CC depends partly on the size of the clearing and on the curing period. In general, the CC for tropical forest clearings is lower than 50% (Balch et al., 2008), but when there is a long (more than a year) lag between slash and burning the CC might increase to 60% and more (Carvalho et al., 2001). The El Niño Southern Oscillation (ENSO) phenomenon may also have a large effect on fuel conditions over tropical regions. Large-scale fires have been shown to occur in South America, Southeast Asia, and Africa in ENSO years, thereby likely increasing CC due to drought conditions (Chen et al., 2011; Field et al., 2009; Hély et al., 2003a).

The 22 unique measurements locations shown in Table 1b cover Brazil (19), Mexico (2), and Indonesia (1). In general, measurement sites were divided into several smaller subplots and the forest was slashed at the beginning of the dry season. The biomass was then weighed using the PIM. After about two months the plots were set on fire and the remaining biomass was weighed within one week after the burn. The average FL for the whole biome was 285±137 t ha^{-1}, CC averaged 49±22%, and total FC was 126±77 t ha^{-1}. Since more than 90% of all measurements were conducted in Brazil (Figure 3), the biome-averaged values are biased towards measurements conducted there. Studies conducted in Mexican and Indonesian tropical forest reported an average FL of 265 and 237 t ha^{-1}, respectively. Surprisingly, the CC of tropical forest in Mexico was the highest of all studies (83% on average), resulting in an average FC of 236 t ha^{-1}, which was significantly higher than values found for both Brazil (117±56 t ha^{-1}) and Indonesia (120±47 t ha^{-1}). However, due to the small number of measurements conducted in Mexico and Indonesia, these findings are not conclusive. Different forest types may partly explain the discrepancy found, and therefore we distinguished between measurements conducted in primary tropical evergreen forest, secondary tropical evergreen forest, and tropical dry forest (Figure 3). To distinguish between tropical dry forests and wooded savannas (Section 2.1), we harmonized with the emission factor compilation of Akagi et al. (2011) in which 60% canopy cover (Hansen et al., 2003) was the delineation between both ecosystems. FL and FC were largest for primary tropical evergreen forests, with average values of 339±104 t ha^{-1} and 143±79 t ha^{-1}, respectively. For secondary tropical evergreen forests these values were substantially lower (101±32 t ha^{-1} and 57±7.0 t ha^{-1}), and comparable with tropical dry forests in South America and Mexico where the average FL was 100 t ha^{-1} and FC 78 t ha^{-1}.

Different fuel categories for the tropical forest biome are presented in Table 2b and can be mainly classified as surface fuels, except for the attached foliage (crown fuels) and rootmat category (ground fuels). Large woody debris (diameter > 20.5cm) and trunks –although not always taken into account in certain studies– correspond to a large part of the aboveground biomass (FL = 147±83 t ha^{-1}), but are usually only slightly burned during a forest clearing process (Carvalho et al., 1995), as shown by an average CC of 32±23% leading to a FC of this category of only 37±32 t ha^{-1}. Similar to the savanna biome, we found a high CC of at least 73% for surface fuels with a large surface area to volume ratio (litter, leaves, and dicots). The small woody fuels (1hr and 10hr) also had high CC, and the CC of the woody debris generally decreased with increasing diameter. From a FC perspective, the most important fuel types in the tropical forest biome were litter (14±8.4 t ha^{-1}) and woody debris size classes with a diameter larger than 0.64cm (15 – 37 t ha^{-1}).

2.3. Temperate Forest

Although accounting for only a small part of the global emissions, temperate forest fires frequently occur nearby the wildland-urban interface with important consequences for human safety and air quality. While tropical fires are largely intentionally ignited to pursue land management goals, the temperate forest is also subject to wildfires. Obtaining FC measurements for wildfires is obviously challenging, so most information is derived from prescribed fires which allow researchers to measure pre-fire conditions. However, these fires may not always be a good proxy for wildfires. For example, wildfires in western conifer forest of the US are often crown fires (while prescribed fires usually only burn surface fuels). Due to potential discrepancies with respect to FC, we distinguished between these fire types in Section 3.2.

The 23 unique FC measurement locations for the temperate forest are from sites in North America (14), Australia (7), Tasmania (1) and Mexico (1), and were taken between 1983 and 2011 (Figure 1). In general, measurements were conducted on sites that were divided into multiple, randomized subplots on which the pre-fire biomass was weighed according to the PIM. The sites were then burned and within a few days after the burn, the post-fire biomass was gathered, dried and weighed.

The biome-averaged FL for the temperate forest biome was 115±144 t ha^{-1}, the CC equaled 61±18%, and fuel consumed by the fire was 58±72 t ha^{-1}. Note that we focused on all measurements presented in Table 1c, so studies that provide information on one specific fuel class only (e.g. ground fuels (Goodrick et al., 2010)) were also included to calculate biome-averaged values. Although CC for North America, Australia and Tasmania were comparable (~60%), the FC showed lower values for North America (49±62 t ha^{-1}) than Australia and Tasmania (78±91 t ha^{-1}). One possible cause of this discrepancy is the contribution of different vegetation types, as elaborated in Figure 4. Measurements in North America were mainly conducted in conifer forest, while eucalypt was the more dominant forest type for Australia and Tasmania. FC for both forest types compare fairly well with the regional averages found, and equaled 48±58 t ha^{-1} for conifers and 79±98 t ha^{-1} for eucalypt forest.

Table 2c shows that litter in the temperate forest had a higher FL and FC than in the tropical forest biome, and the average FC for this surface fuel category equaled 17±9.9 t ha^{-1}. The different woody debris classes had a similar pattern as found for the savanna and tropical forest biome, with decreasing CC for categories with increasing fuel diameters. However, an interesting difference was found in the biggest size class: sound woody debris had a low CC (38±42%), while the fraction of rotten woody debris consumed by the fire was very high (96±5.4%), resulting in an average FC of

20±4.8 t ha^{-1} for this category. Although this difference was observed in a few other studies as well, little research is available on comparing the physical and chemical properties of sound and rotten woody debris, which is likely to affect the FC (Hyde et al., 2011). The most important fuel category from a FC perspective was organic soil, with an average value of 25±31 t ha^{-1}. For the same reason as explained in Section 2.1, a small discrepancy was found between the total FC sum of different fuel categories (77 t ha^{-1}) and the biome average (58±72 t ha^{-1}).

2.4. Boreal Forest

Fires in the boreal (high latitudes of about 50 to 70°) forest are thought to be mostly natural (wildfires) due to the vast size of the forest region, the low population densities and the difficult accessibility. However, much of the Asian boreal forests are disturbed by (il)legal logging activities (Vandergert and Newel, 2003) which can increase fire activity in more remote regions (Mollicone et al., 2006). Approximately two-thirds of the boreal forests are located in northern Eurasia, while the remainder is in North America. The circumpolar boreal fire regime is characterized by large forest fires, although fires in North America are in general larger and less frequent than the ones in Eurasia (de Groot et al. 2013a). North American boreal fires are characterized by high intensity crown fires, while fires in boreal Russia are more often surface fires of lower intensity (Amiro et al., 2001; Soja et al., 2004; Wooster et al., 2004, de Groot et al. 2013a). Canada has a very long fire record, starting in 1959, while the record for Alaska starts in 1950 (Kasischke et al., 2002). Since 1990, 2.65 million ha year^{-1} burned in the North American boreal forest, with high year-to-year variability (Kasischke et al., 2011). FL in the boreal forests depends for a large part on tree species, stand density, climate, topography, moisture, seasonal thawing of permafrost and time since last burn. In many forest types, dead material accumulates in deep organic soil horizons due to the slow decomposition rates. CC in organic soils is mostly controlled by conditions that control surface soil moisture, including topography, seasonal thawing of permafrost, and antecedent weather conditions. When dry conditions prevail, such as during high-pressure blocking event that can last for few days to several weeks over North America (Nash and Johnson, 1996), much of the forest floor can burn, and depths of 30 cm or more can be reached. There is a strong relation between moisture content and fuel bed depth on the one hand and forest floor consumption on the other hand (e.g. de Groot et al., 2009). Of all global fire regimes, the boreal forest is most susceptible to climate change due to polar amplification of temperature increase (Flannigan et al. 2013; de Groot et al. 2013b). For example, the area burned by lightning fires in the North American Boreal region has doubled between 1960 and 1990 (Kasischke and Turetsky, 2006).

Field measurements described in literature were almost all conducted in boreal North America (35 in total), except for three measurement sets that came from boreal Asia (Figure 1, Table 1d). The general method for determining FL and FC was to apply the PIM. Approaches have also been developed to estimate consumption of surface organic layer fuels by estimating the pre-and post-fire thicknesses and density of surface organic horizons (de Groot et al. 2009; Turetsky et al., 2011).

We estimated a biome-averaged FL of 69±61 t ha^{-1}, substantially lower than the average FL for the temperate forests. Average FL for this biome is for upland forest types. However, deep peatland deposits (see section 2.10) cover about 107 M ha (Zoltai et al. 1998) or 18% of the North American boreal forest zone (Brandt, 2009) and 16% of the northern circumpolar permafrost soil area (Tarnocai et al., 2009). By contrast, peatlands only cover about 0.07 M ha in the temperate zone, which has higher FL overall. Despite low decomposition rates due to a cold, moist climate, the lower FL in the boreal forest region is primarily a result of slower tree growth rates (biomass accumulation) and frequent to infrequent fire disturbance that can remove substantial amounts of fuel. The average CC was 51±17%, and the FC equaled 35±24 t ha^{-1}. Similar as for the temperate forest, we included all measurements (presented in Table 1d) to calculate the biome-averaged values. The representativeness of these values for wildfires and prescribed fires is discussed in Section 3.2. Differences between boreal North America and Siberia were observed, but it should be noted that only 3 studies provided a FC estimate for Russia. Values on FL, CC, and FC were overall higher for boreal fires in North America than the field studies in Russia (Figure 5).

Information on fuel categories is presented in Table 2d, as well as in Figure 5. Different classification systems were sometimes used for boreal fuels, and therefore it was difficult to extract the right information for ground, surface and crown fuels (further discussed in Section 3.4). Moreover, it was not always clear is which class certain fuels are consumed: e.g. organic material can be consumed on the ground but also in a crown fire (Hille and Stephens, 2005). The highest FL (50±29 t ha^{-1}) and FC (32±26 t ha^{-1}) in the boreal forest biome was found for ground fuels, mainly consisting of organic soils. Moreover, a difference in organic matter FL in permafrost and non-permafrost regions was found (56 and 86 t ha^{-1}, respectively). However, due to a CC of 62 and 41% for permafrost and non-permafrost regions, the FC for both regions was equal (35 t ha^{-1}). Finally, slope aspect has been shown to have an effect as well, with the south facing slopes having the highest FL and FC due to warmer and drier conditions that better favour plant growth and fire intensity than shadowed north faces (Viereck et al. 1986; Turetsky et al., 2011). As with most of our findings, however, the number of studies is far too low to evaluate whether this is also the case in general.

2.5. Pasture

Fires related to agricultural practices were divided into shifting cultivation (Section 2.6), the burning of crop residues (Section 2.7) and pasture burning. The latter type of burning often follows tropical deforestation fires and is used to convert land into pasture. Prior to this conversion, lands can be used in shifting cultivation as well. Typically, landowners set fires every 2-3 years to prevent re-establishment of forests (Kauffman et al., 1998) and to enhance the growth of certain grasses (Fearnside, 1992). In general, these fires mostly consume grass and residual wood from the original forest. Pasture fires are most common in the Brazilian Amazon where many cattle ranches have been established in areas that were previously tropical forest. Although less abundant, these 'maintenance' fires occur also in tropical regions of Africa, Central America and Asia.

The pasture measurements presented in Table 1e represent 5 unique measurement locations and cover 2 different continents (Figure 1). Pasture had an average FL, CC, and FC of 74±34 t ha^{-1}, 47±27%, and 28±9.3 t ha^{-1}, respectively. Regional discrepancies for FC were found though, with FL for Brazilian pastures (84±29 t ha^{-1}) being substantially higher than found in Mexico (35 t ha^{-1}). However, FC values compared reasonably well for both regions (30±10 and 24 t ha^{-1} for Brazil and Mexico, respectively).

2.6. Shifting cultivation

Shifting cultivation is commonly practiced in Africa, Central America, South America and Asia. In general, lands are cultivated temporarily (often for only a few years) before soil fertility is exhausted or weed growth overwhelms the crops. The lands are then abandoned and may revert to their natural vegetation, while the farmers move on to clear a new fields elsewhere. The land is slashed and burned, which leaves only stumps and large trees in the field after the fire (Stromgaard, 1985). Apart from the fact that fire is an easy and cheap tool to clear the land, it has the further advantage that the ashes will also (temporarily) enrich the soil.

For shifting cultivation fires the average FL was 44 with a range of 14 to 75 t ha^{-1}, the CC equaled 47 [30-64]%, and FC was 23 [4-43] t ha^{-1}. Note that these values are based on the measurements of two studies only (Figure 1, table 1f). The two shifting cultivation studies showed a remarkable difference: FC of Indian tropical dry deciduous forest (4.0 t ha^{-1}; Prasad et al., 2000) was one order of magnitude lower than for shifting cultivation practices in wooded savanna of Zambia (43 t ha^{-1}; Stromgaard, 1985). Due to the relatively small number of measurements, these findings are not conclusive.

2.7. Crop residue

Crop residue burning is a common practice to recycle nutrients, control pests, diseases, weeds and in general to prepare fields for planting and harvesting. The main crop residue types that burn are rice, grains (i.e., wheat) and sugarcane, but burning is not limited to these crop types. FL is highly variable, as it depends on both the type of crop burned and the method used for harvesting the crop (mechanized, manual, etc.). Detecting these fires using global burned area products is difficult as in general cropland fires are small and the land can be tilled and replanted quickly after burning (making it difficult to observe the latency of burned ground as is common in less managed and/or more natural landscapes). Moreover, the fuel geometry varies globally from short-lived burning of loose residue in the field to long-lasting smoldering combustion of small hand-piles of residue, and both are hard to detect from space. Traditional methods to obtain estimates for agricultural fires are the use of governmental statistics on crop yield (e.g. Yevich and Logan, 2003), residue usage for cooking and livestock (the leftovers are assumed to be burned), field measurements, or using agronomic data (e.g. Jenkins et al., 1992).

On average, crop residue burning had a FL of 8.3±9.9 t ha^{-1}, CC of 75±21% and FC of 6.5±9.0 t ha^{-1} (Table 1g). We estimated an average FL of 23 t ha^{-1} for Brazilian sugarcane (Lara et al., 2005) by using a CC of 88% as reported by McCarty et al. (2011). FC values for different US crop types (McCarty et al., 2011) were used to derive crop-specific FL data (French et al., 2013) and CC values were taken from expert knowledge from agriculture extension agents in Arkansas, Louisiana, Florida, Kansas, and Washington during field campaigns in 2004, 2005, and 2006, as well as from the scientific literature (Dennis et al., 2002; Johnston and Golob, 2004). CC variables ranged from 65% for cotton and sugarcane and 85% for wheat and bluegrass, which are lower but within the range of the CC value (-23 to -3% less than CC of 88%) used by the Environmental Protection Agency (EPA) of 88% (EPA 2008 GHG).

FC values varied between different crop types, as shown in Figure 6. For US crops the highest FC was found for seedgrass (10 t ha^{-1}) and rice (8.8 t ha^{-1}), while values for soybeans (0.5 t ha^{-1}) and corn (1.0 t ha^{-1}) were lower. In general, US crop values are assumed in the analysis to be approximately representative of other developed agricultural areas like Brazil and Russia (McCarty et al., 2012), but uncertainty increases for less industrialized agricultural areas in Africa and Asia. However, Brazilian sugarcane (20 t ha^{-1}) was found to have a FC that is more than twice as high as sugarcane in the US (8.0 t ha^{-1}). More measurements are needed to confirm this discrepancy.

2.8. Chaparral

Chaparral vegetation is a type of shrubland that is primarily found in southwestern US and in the northern portion of the Baja California (Mexico), but similar plant communities are found in other Mediterranean climate regions around the world like Europe, Australia and South Africa. Typically, the Mediterranean climate is characterized by a moderate winter and dry summer, which makes the chaparral biome most vulnerable to fires in summer and fall (Jin et al., 2014). In California, the combination of human ignition, the large wildland-urban interface, and extreme fire weather characterized by high temperatures, low humidities, and high offshore Santa Ana winds (Moritz et al., 2010) may lead to large and costly wildfires (Keeley et al., 2009).

We found 2 studies covering 5 different measurement locations in southwestern US (Table 1, Figure 1h). Since Cofer III et al. (1988) only provided a FC for chaparral burning, we used a CC of 76% (average CC from studies of Hardy et al. (1996) and Yokelson et al., 2013) to derive a FL estimate for the Cofer et al. (1988) study. We then used the FL values of all 3 studies to estimate the biome average FL of 40±23 t ha^{-1}. The CC equaled 76%, yielding an average FC of 27±19 t ha^{-1}.

2.9. Tropical Peat

Tropical peatland has only recently been recognized as an important source of biomass burning emissions. Roughly 60% of the worldwide tropical peatland is located in Southeast Asia and more specifically in Indonesia (Rieley et al., 1996; Page et al., 2007). Peat depth is an indicator for the total biomass stored in peatland, but only the peat layer above the water table can burn. Drainage and droughts lower the water table, adding to the total FL. On top of that, living biomass and dead above ground organic matter also contribute to the FLs in these peatlands. The bulk density and carbon content of peat are of importance to determine the amount of carbon stored. The average density is around 0.1 g cm^{-3} and the carbon content ranges between 54-60% (Page et al., 2002; Riely et al., 2008; Ballhorn et al., 2009; Stockwell et al., 2014). The depth of burning is the key factor that determines the total FC, but information about it is scarce. Results from several field measurements indicate a link between this burning depth and the depth of drainage (Ballhorn et al., 2009). Commercial logging in drained peat swamps has increased their susceptibility to fire, especially during droughts (such as during and ENSO event).

In total 4 studies provided data on tropical peatland measurements in Indonesia (Table 1i). In general, post-fire observations of the average burn depth were combined with pre-fire conditions reconstructed from adjacent unburned patches to determine the FC. Tropical peatland (including peat soils and overstory) had the highest FC of all biomes, with an average of 314±196 t ha^{-1}. Only two studies provided data on FL and CC, and since the study of Saharjo and Nurhayati (2006) focused on litter and branches only, a CC of 27% (Usup et al., 2004) was found to be representative for the tropical peat biome. Taking a CC of 27%, the biome-averaged FL equaled 1056±876 t ha^{-1}, thereby having the highest FL of all biomes. However, due to limited information on CC measured in the field there is no clear definition of the average FL for tropical peat. Note that the measurements taken by Ballhorn et al. (2009) were using Laser Imaging, Detection And Ranging (LIDAR) aerial remote sensing, and the study of Page et al. (2002) relied on field measurements combined with information obtained from Landsat Thematic Mapper (TM) images.

2.10. Boreal Peat

The northern peatlands are a result of the slow decomposition of organic material over thousands of years. Traditionally, northern peatlands have been considered as a slow, continuous carbon sink. However, the vulnerability of this region to global warming and the resulting increase in wildland fires has challenged this idea (Zoltai et al., 1998; Harden et al., 2000; Turetsky, 2002). There are still large uncertainties associated with the FL and CC of peat fires. The depth of fires is not well documented, leading to large uncertainties in the total FC estimates. In some cases water table depth may serve as a proxy for determining the depth of burning. However, also the susceptibility of peatlands to fire during different moisture conditions is poorly documented at best. This makes modeling peat fires very difficult and stresses the importance of more field measurements.

Two measurements were taken between 1999 and 2001 in boreal Canada (Table 1j). On each burn site, multiple plots were established and information on the peat density (which is assumed to increase nonlinearly with depth) was used in combination with the burn depth to determine the FC. No data on FL and CC were provided, but the average FC of the two studies is 43 [42-43] t ha^{-1}. A standard deviation of 25 t ha^{-1} (Turetsky and Wieder, 2001) can be used as the average uncertainty for the boreal peat biome. Turetsky and Wieder (2001) showed that FC of permafrost bogs (58 [43-72] t ha^{-1}) is more than twice as high as continental bogs (27 [11-42] t ha^{-1}). A similar difference was found for hummocks and hollows, which are raised peat bogs and lows, respectively: FC for hummocks was 29±2.0 t ha^{-1}, while fires in hollows consumed on average 56±6.0 t ha^{-1} (Benscoter and Wieder, 2003).

2.11. Tundra

The Arctic tundra stores large amounts of carbon in its organic soil layers that insulate and maintain permafrost soils, although these soil layers are shallower than those found in peatlands and boreal forests. While the region is treeless, some vegetation types include a substantial shrub component where additional carbon is available for burning. On Alaska's North Slope approximately 10% of the land cover is shrub dominated (>50% shrub cover), while the remainder is dominated by herbaceous vegetation types (Raynolds et al., 2006). Fire regime in the Arctic is largely unknown, but historically fire is generally absent in the tundra biome compared to other biomes. However, the evidence of increasing fire frequency and larger extent of the fires in the arctic (Hu et al., 2010) may represent a positive feedback effect of global warming, so in the future more fires may occur in this biome (Higuera et al. 2011). There are still large unknowns of the impacts that fires have on the carbon stocks of the tundra ecosystems. Even the topsoil layers in the tundra store large pools of carbon in organic-rich material. This removal of the topsoil may also expose the permafrost layers to heating by the warm summer temperatures, thawing the ground and destabilizing the tundra carbon balance.

The only measurements found in the literature of FC in the tundra biome are from the Anaktuvuk River fire in 2007 (Mack et al., 2011). The measurements were taken on twenty sites in the burned area and the pre-fire peat layer depth was reconstructed to determine the pre-fire FL. The FL was on average 165±15 t ha^{-1}, and averaged CC and total FC was respectively 24±5.0% and 40±9.0 t ha^{-1} (Table 1h). These measurements represent a thorough effort to document FC, but still represent just one fire that is considered to be a fairly high severity event (Jones et al., 2009). Other measurements of surface FC at fires in the Noatak region of Alaska and a recent burn on the Alaskan North Slope showed minimal organic surface material loss (N. French, unpublished data). These fires may represent more typical fire events with more moderate consumption than was found in the Anaktuvuk River fire. There is no doubt that the lack of sufficient field measurements in the tundra biome means a reasonable estimate of FC in tundra fires is not fully known. While the Anaktuvuk River fire measurements are of value, there should be caution in using these data to generalize since the event represents a more severe event than many fires in the region. They may, however, be indicative of how future fires in the region may impact carbon losses as the region experiences increased fire frequency and severity.

3. Discussion

3.1. Spatial representativeness of fuel consumption measured in the field

Due to the spatial heterogeneity in fuels and the limited amount of measurements one important question to ask is: How representative are the biome-average values presented in this review? Field measurements of FC were spatially well represented in the major biomass-burning regions, like the Brazilian Amazon, boreal North America and the savannas areas in southern Africa. However, several other regions that are important from a fire emissions perspective were lacking any measurements, and these include Central Africa (e.g. Congo, Angola, but also regions further north such as Chad and southern Sudan), Southeast Asia and eastern Siberia (Figure 1). Due to these spatial gaps, it remains uncertain whether measurements of FL, CC, and FC as presented in this study are representative for the whole biome. As mentioned for the 'Tundra', where fire may become increasingly important as the region warms, the one set of field samples included in this review may not be a representative of past and future fire.

Within biomes differences were found to be large for certain regions, as shown in Figures 2-5. For example, we found substantial differences in FL and FC for boreal areas, with Russian sites having lower values compared to the ones in North America (Figure 5). This difference might be due to different burning conditions in both regions, with a larger contribution of surface fuels and less high-intensity crown fires occurring in boreal Russia (Wooster et al., 2004). Although available literature data showed that FC for crown fuels was indeed higher than for surface fuels, more data for especially boreal Russia is needed to confirm this line of thought. Moreover, Boby et al. (2010) and Turetsky et al. (2011) showed that the timing of FC measurements (early dry seasons versus late dry season) contribute to different boreal FC values as well. In general, both FC and CC may increase over the course of the dry season as large diameter fuels dry out. This was also suggested by Akagi et al. (2011) for the savanna biome, and consistent with a seasonal decrease in MCE as proposed by Eck et al. (2013).

Regional differences were also found for the tropical forest biome, where almost all measurements were conducted in the Brazilian Amazon, with a few exceptions for Mexico, and Indonesia. Southeast Asia (Myanmar, Vietnam, Laos, and Cambodia) was lacking any FC measurements described in the peer-reviewed literature, but this region is important from a fire emissions perspective. Tropical forests in Mexico had a higher CC than forests in the Amazon and Indonesia (Figure 3), and had a higher FC as well. Different forest types can likely explain this difference; in Figure 3 substantial differences are shown for FL, CC, and FC in primary tropical evergreen forest, secondary tropical evergreen forest, and tropical dry forest. Obviously, the amount of measurements conducted in a specific forest type will impact the biome-averaged value found for a certain region. Clearly, the definition of a certain biome is not always straightforward, and uncertainty regarding regional discrepancies within the different biomes should be taken into account when averaged values are interpreted and used by the modeling communities.

Coming back to the question posed in the beginning of this section, we think care should be taken with using biome-average values. They provide a guideline but the path forward is to continue developing models or remote sensing options that aim to account for variability within biomes, and use the database accompanying this paper to constrain these models, rather than to simply use biome-average values (further discussed in Section 3.2). Use of FC for specific vegetation types within broader biomes (like the different crop types as presented in Figure 6) or fuel categories offers an interesting alternative, and is further discussed in Section 3.4.

3.2. Field measurement averages and comparison with GFED3

Although the definition of a certain biome is not always straightforward, the biome-averaged values that we presented in this paper are still valuable to highlight differences in fire characteristics between regions with specific vegetation and climate characteristics. We compared our work with estimates from the Global Fire Emissions Database version 3 (GFED3) and several FRE-derived studies (Section 3.3). GFED3 fire emissions estimates (monthly 0.5°×0.5° fields) are based on estimates of burned area (Giglio et al., 2010) and the satellite-driven Carnegie-Ames-Stanford Approach (CASA) biogeochemical model (van der Werf et al., 2010). To calculate FC we divided the GFED3 total biome-specific emissions estimates (g Dry Matter) in every modeling grid cell by the total burned area observed for every grid cell. Since one grid cell may consist of multiple biomes we followed the GFED3 fractionation of emissions estimates, which represents the contribution of a certain biome to total emissions within one grid cell. Biome-specific information on the area burned within one grid cell was not available, and therefore we assumed that burned area followed the same fractionation as the GFED3 emissions estimates. This assumption may over- or underestimate biome-averaged GFED3 FC values: For example, in a deforestation grid cell that consists of savannas and tropical evergreen forests, the contribution of savanna fire emissions to total emissions can be small, even when the contribution of savanna burned area to total burned area observed in a grid cell is actually quite large. In this specific case - when assuming that burned area followed the same fractionation as the emissions- the estimated FC of savannas would be overestimated.

In Table 3 an overview is given for biome-specific FL, CC, and FC that we estimated from data found in literature. In the fifth column FC per unit burned area of GFED3 is shown for the collocated grid cells, i.e. grid cells in which measurements were taken, and the sixth column presents the difference between GFED3 FC and the field measurements. In general, substantial differences were found between co-located GFED3 FC and the field measurements. Although the average FC agreed reasonably well (<40%) for crop residue, tropical peat and the boreal peat biome, much large discrepancies (>59%) were found for the other biomes. Many field measurements for these biomes had a standard deviation that was close to the measurement average, indicating that uncertainty is substantial.

Within the savanna biome GFED3 overestimated the FC by 72% compared to the measurements, and this overestimation was even higher for grassland regions (78%). A possible cause for these discrepancies is that field campaigns tend to focus on frequently burning areas, so fuels do not have the time to build up and increase their FL (van der Werf et al., 2010). Because of the relatively coarse 0.5° resolution of GFED3, the fire frequency in GFED is the average of more and less frequently burning patches, and thus potentially longer than in field sampling sites. On the other hand, only a very small portion of the land's surface burns annually (van der Werf et al., 2013). Improved resolution for the models may help to alleviate this problem and bring model values closer to the field measurements, although it is very unlikely this is the only reason for the noted discrepancy.

For tropical forests, an important biome due to large-scale deforestation emissions, substantial differences were found as well: GFED3 overestimated FC by 71% compared to the field measurement average for collocated grid cells. This discrepancy may be partly explained by the fact that repeated fires in the tropical forest domain (when forest slash that did not burn in a first fire is subject to additional fires during the same dry season) are not always included in the field measurements. Within GFED3, on the other hand, these repeated fires were modeled by the number of active fires observed in the same grid cell (fire persistence), which yields information on the fuel load and type of burning (Morton et al., 2008; van der Werf et al., 2010). Regional differences within the biome, as discussed in Section 3.1, will also contribute to the differences found: In our case the field measurement average was biased towards evergreen tropical forests fires, but when the emphasis is put on fires in secondary or tropical dry forest this average value could change significantly (Figure 3). It is likely that grid cell heterogeneity in tropical deforestation regions explains the large discrepancy found for the pasture biome, where GFED3 FC overestimated the field measurements by almost 500%. For these specific pasture grid cells GFED3 may have been biased towards tropical evergreen deforestation fires, thereby increasing the average FC.

In the temperate forest biome FC was underestimated in GFED3 by 74% compared to the field measurement average for collocated grid cells. In our averaged field measurement estimate we included all measurements presented in Table 1c. As noticed in Section 2.3, it is likely though that studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels) are more representative for wildfires. Prescribed burns, on the other hand, tend to burn less fuel and therefore the studies that only include ground or surface fuels were probably more representative for this fire type. When focusing on studies that provide information on one specific fuel class only, the field average for the temperate forest would be significantly lower (13±12 t ha^{-1}) as well as the discrepancy with GFED3 (+14%). This FC value of 13 t ha^{-1} may be more realistic for prescribed fires, which contribute to roughly 50% of all temperate forest fire emissions in the contiguous United States (CONUS). Still, it remains very uncertain how well FC measured for specific fuel classes is representative for prescribed fires and wildfires. This issue also counts for boreal forests, where GFED3 overestimated the field measurements by almost 80%. When only including studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels), the field average for the boreal forest would increase from 35±24 t ha^{-1} to 39±19 t ha^{-1} and the discrepancy with GFED3 would decrease (from +79 to +60%). This value of 39±19 t ha^{-1} may be more representative for boreal wildfires. Note that for temperate and boreal forest measurements sometimes the more restrictive definition of FL (as presented in Section 1) was used, and this can have an impact on FC values as well; if one applies a CC calculated with respect to a restrictive pre-fire FL to total biomass available, the overall FC that was estimated can be too high.

For most biomes, a few field measurements had a FC that was an order of magnitude larger than the other values listed in Table 1, which explains the discrepancy between the median and average FC values that was sometimes found (e.g. the 'Australia and Tasmania' region in Figure 4). By neglecting these 'outliers' the biome-averaged values may change significantly, but this could lead to erroneously low or high estimates as well. In general, FC shows large variability between biomes, within biomes, and even within a specific fuel type. FC is often hard to measure, and since only a few measurements are available for some biomes, care should be taken when using the biome-averaged values presented in this paper.

3.3. Field measurement averages and comparison with FRE derived FC estimates

Besides a comparison with GFED3 data, we performed a comparison of field measurement averages with fire radiative energy (FRE, time-integrated FRP) derived estimates as well. The basis of the FRE approach for estimating FC is that the heat content of vegetation is more or less constant, and that the FRE released and observed through a sensor can be converted to FC by the use of a constant factor, which was found to be 0.368±0.015 kg MJ^{-1} across of a range of fuels burned under laboratory conditions (Wooster et al., 2005). More recent field experiments, however, indicated that the conversion factor might be slightly lower for grasslands in North America (Kumar et al., 2011; Schroeder et al., 2014). Smith et al. (2013) investigated the relationship between FC and FRE for pine needles with different fuel moisture contents, and found that FRE released per kilogram biomass consumed decreased with fuel moisture content due to the energy required to evaporate and desorb the water contained in the fuel. Thus, corrections for FRE based FC assessments may be needed for fuels that burn at higher fuel moisture contents. Differences in heat content of fuel may introduce additional variation: For example, a clear relationship between FRE and FC has not yet been demonstrated for fires that burn mostly in the smoldering stage, like organic soils in boreal forests or large woody debris and trunks in tropical deforestation regions. Another potential source of uncertainty in the relation between satellite-derived FRE and FC is the correction for atmospheric disturbances, which may significantly alter FRP retrievals and hence estimates of FC (Schroeder et al., 2014). Note that, currently, atmospheric correction is not performed for the standard fire products derived from MODIS. Moreover, Schroeder et al. (2014) also indicate that cloud masking in the MODIS FRP product may lead to FRP underestimates as hotspots under thick smoke may be erroneously masked out.

Despite all these uncertainties this approach is promising and there is a number of studies that relate FRE to FC on regional (Roberts et al., 2011; Freeborn et al., 2011) to global scales (Vermote et al., 2009; Ellicott et al., 2009), and Kaiser et al. (2012) used FRE to represent biomass burning in an operational chemical weather forecast framework. However, since such estimates can be derived independently of burned area, only a limited number of studies allow a straightforward comparison to the FC values given in mass units per area burned from the field experiments used in this study.

A common finding of FRE-based estimates is that FC is generally lower than GFED estimates, as shown by Roberts et al. (2011) who estimated FC for Africa through an integration of MODIS burned area and Meteosat Spinning Enhanced Visible and Infrared Imager (SEVIRI) derived FRP and found values that were about 35% lower than GFED. For the savanna biome a median FC of ~4 t ha^{-1} was found for grassland and shrubland. This corresponds relatively well with the mean of 4.3±2.2 t ha^{-1} and 5.1±2.2 t ha^{-1} found in grassland savanna and wooded savanna field studies we compiled, respectively. Boschetti and Roy (2009) explored temporal integration and spatial extrapolation strategies for fusing MODIS FRP and MODIS burned area data over a single large fire in a grassland dominated area with sparse eucalypt trees in northern Australia. They estimated a FC range of 3.97-4.13 t ha^{-1}, which is well within the range found in the Australian FC studies summarized in Table 1. Kumar et al. (2011) exploited properties of the power law distribution to estimate FC from FRP for an Australian savanna and a study area in the Brazilian Amazon. While their FC estimate of 4.6 t ha^{-1} of the Australian site is similar to the temporal integration results of Boschetti and Roy (2009), the estimate for the Brazilian site is above 250 t ha^{-1} and thus substantially higher than the biome-averaged value for Brazilian tropical forest (117±56 t ha^{-1}).

In general, realistic values are often obtained for well-observed fires, but unrealistically low or high values can often occur especially for smaller fires due to the sparseness of FRP observations and inaccuracies in the temporal interpolation and the burned area estimates. While FRE seems to provide realistic estimates under a range of conditions, issues of undersampling of FRE and -maybe less important - the conversion of FRE to FC still remain to be addressed more completely in order to derive spatially explicit FC estimates using the FRP approach.

3.4. Fuel consumption for different fuel categories

As discussed in Section 3.1, the interpretation of average FC values for each biome should be done carefully. As an alternative to biome-averaged values, we also provided FC for specific fuel categories, which may be more useful for certain research areas or modeling communities. In Table 2 fuel category information was presented for the savanna, tropical forest, temperate forest and boreal forest biome. We focused on the main fuel categories found in literature, and classified these according to the US classification system. Most of these fuel categories were similarly defined in different studies and biomes, the woody debris classes for example were systematically based on their time lag. However, for measurements conducted in boreal forests the definition of woody fuel classes was less consistent, mainly due to differences between Canadian and American sampling methodologies (Keane, 2012). Especially the difference between surface and ground fuels can be therefore vague: e.g. litter is classified as surface fuel according to the US fire management standards, while many Canadian studies define litter and organic soils as the forest floor and thus ground fuel class. Obviously, this can cause problems when comparing studies, and therefore we recommend a more uniform measurement protocol for this fuel type and biome.

Certain fuel type averages presented in this paper were based on a minimum of 3 different studies. For these fuel categories specifically, more field measurements are needed to decrease the uncertainty and better understand the variations found, especially within the boreal and tropical forest biomes. Measurements in the boreal and tropical peat biomes deserve specific attention in future measurement campaigns: although peat fires have been studied in several field campaigns, they still remain one of the least understood fire types due to poor knowledge of the depth of the burning and the complex mix of trace gases emitted in these fires as a consequence of the belowground combustion that is less efficient than during surface or crown fires. Additional studies are needed in order to fully capture the variability and processes occurring in these biomes, especially considering their large FL and FC. Another biome that deserves more attention in future studies is crop residue, since our understanding of FC variability for different crop types is still poor.

4. Summary

This study aimed to compile all peer-reviewed literature on measured fuel consumption in landscape fires. The field measurements were partitioned into 11 different biomes, and for each biome we have reported biome averages and other statistics. For some biomes we provided information on different fuel categories as well. The number of study sites varied from 1 for the tundra biome, to 39 different measurement sites in the boreal forest biome. In total we compiled 124 unique measurement locations. The biome-averages and fuel type specific data of fuel load and fuel consumption can be used to constrain models, or be used as an input parameter in calculating emissions. Care should be taken though with using biome-averaged values because it is unclear whether these are representative and because there is substantial variability within biomes, as indicated by the large standard deviations found.

Modeled values from GFED3 corresponded reasonably well with the co-located measured values for all biomes except the savanna and tropical forest where GFED-derived values were over a factor two too high. In tropical forests, part of this discrepancy can be explained because field measurements only take one fire into account, while GFED also accounts for consecutive fires which boost fuel consumption.

Although the overall spatial representativeness of the fuel consumption field measurements was reasonable for most fire-prone regions, several important regions from a fire emissions perspective –including Southeast Asia, Eastern Siberia, and Central Africa– were severely under represented. When new information on fuel consumption becomes available, the field measurement database will be updated. The most up-to-date version can be retrieved from http://www.globalfiredata.org/FC. As a next step, we aim to improve our understanding of the drivers of regional and temporal variability within biomes, as well as for different fuel categories.

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Figures

Figure 1: Fuel consumption field measurement locations for different biomes. Background map shows annual GFED3 fire C emissions in g C m^{-2} $year^{-1}$, averaged over 1997-2009.

Thijs van Leeuwen 13/10/2014 19:34
Comment [1]: New measurement sites were added

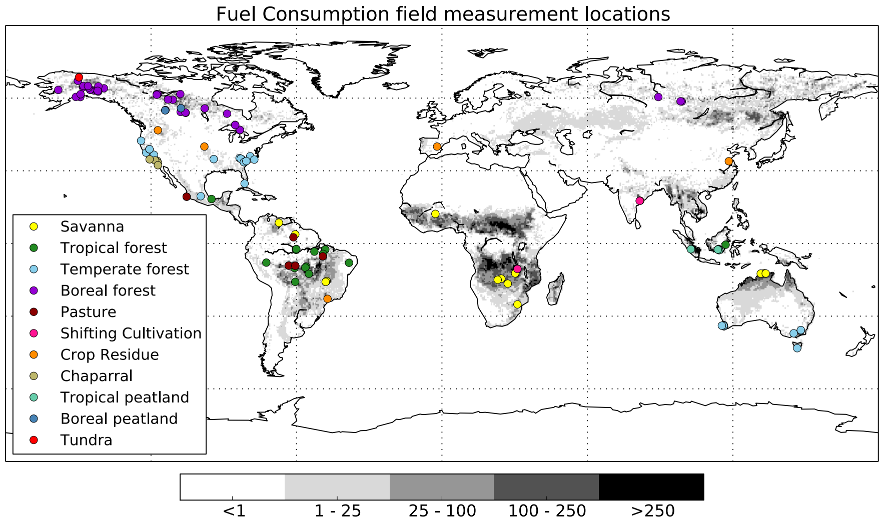


Figure 2: Overview of field measurements of fuel load (FL), combustion completeness (CC), and fuel consumption (FC) in the savanna biome. The pie charts on top correspond to the amount of unique measurement locations for different geographical regions (left) and vegetation types (right), and in the box plots below field averages of FL, CC, and FC are presented. The boxes extend from the lower to upper quartile values of the measurement data, with a line at the median and a black filled circle at the mean. The whiskers extend from the box to show the range of the data, and outliers are indicated with pluses.

Thijs van Leeuwen 13/10/2014 19:34
Comment [2]: Legend changed to 'Grassland savanna' and Wooded savanna'

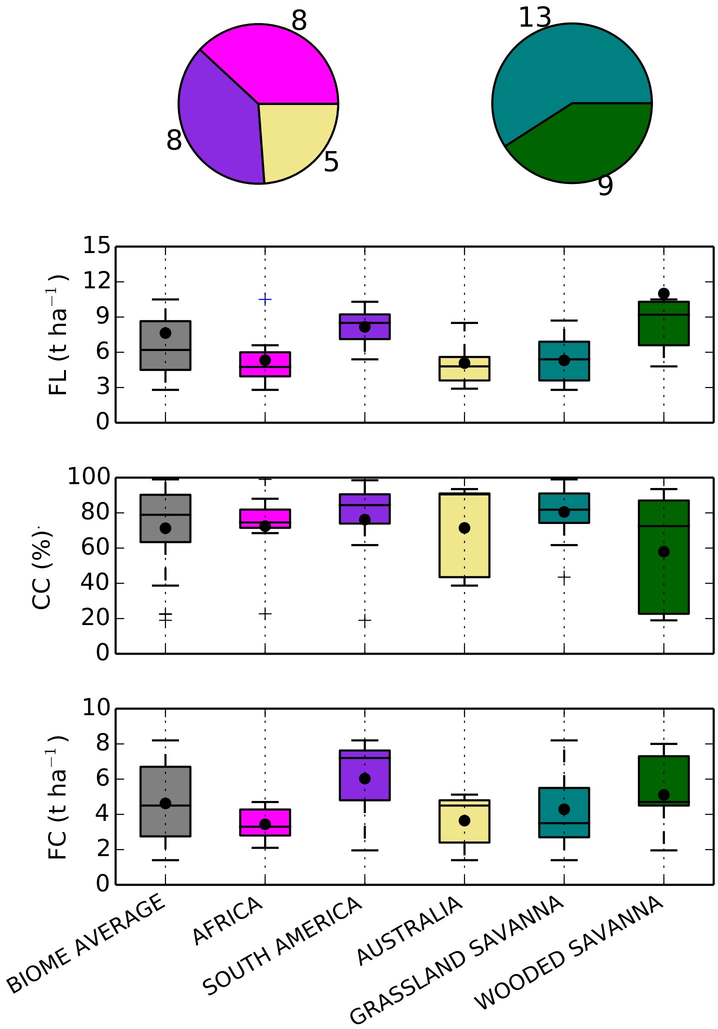


Figure 3: Overview of field measurements of fuel load (FL), combustion completeness (CC), and fuel consumption (FC) in the tropical forest biome. The pie charts on top correspond to the amount of unique measurement locations for different geographical regions (left) and forest types (right), and in the box plots below field averages of FL, CC, and FC are presented. The boxes extend from the lower to upper quartile values of the measurement data, with a line at the median and a black filled circle at the mean. The whiskers extend from the box to show the range of the data, and outliers are indicated with pluses.

Thijs van Leeuwen 13/10/2014 19:33
Comment [3]: Pie charts were adjusted

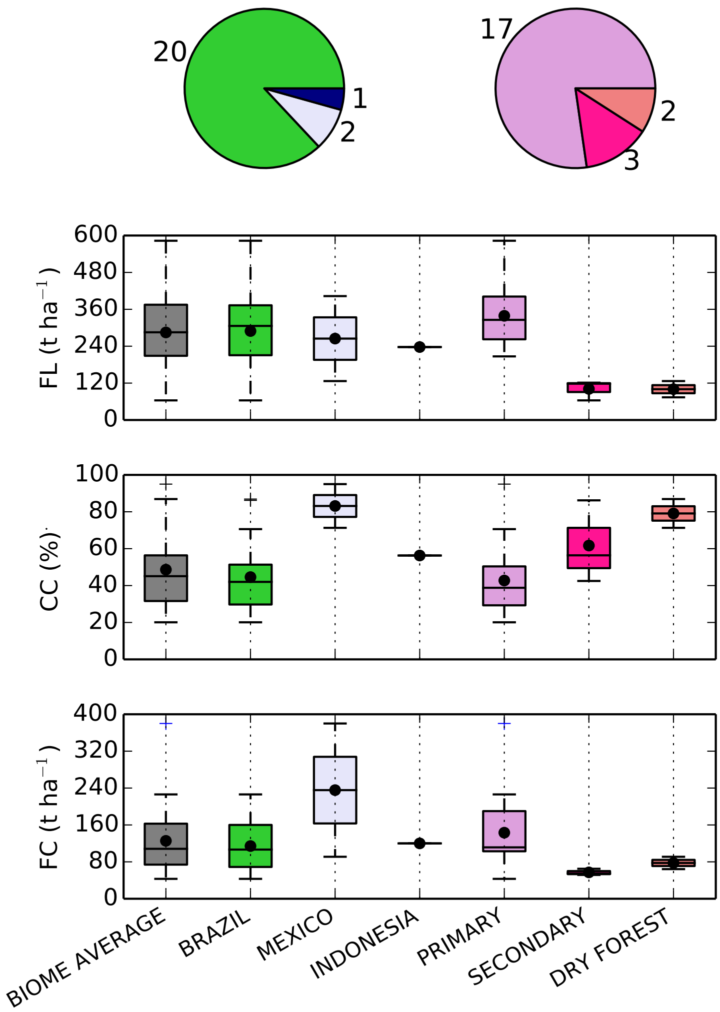


Figure 4: Overview of field measurements of fuel load (FL), combustion completeness (CC), and fuel consumption (FC) in the temperate forest biome. The pie charts on top correspond to the amount of unique measurement locations for different geographical regions (left) and forest types (right), and in the box plots below field averages of FL, CC, and FC are presented. The boxes extend from the lower to upper quartile values of the measurement data, with a line at the median and a black filled circle at the mean. The whiskers extend from the box to show the range of the data, and outliers are indicated with pluses.

Thijs van Leeuwen 13/10/2014 19:32
Comment [4]: Biome-averaged values for North America, Australia, Eucalypt forest, and Conifer forest were changed

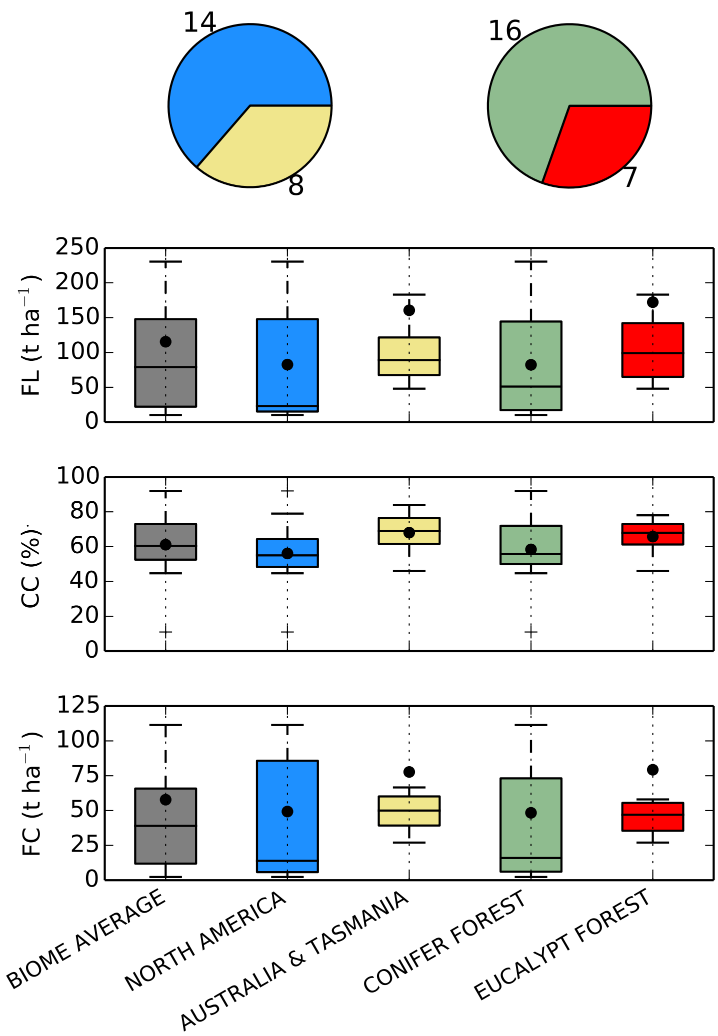


Figure 5: Overview of field measurements of fuel load (FL), combustion completeness (CC), and fuel consumption (FC) in the boreal forest biome. The pie charts on top correspond to the amount of unique measurement locations for different geographical regions (left) and fuel classes (right), and in the box plots below field averages of FL, CC, and FC are presented. The boxes extend from the lower to upper quartile values of the measurement data, with a line at the median and a black filled circle at the mean. The whiskers extend from the box to show the range of the data, and outliers are indicated by blue pluses.

Thijs van Leeuwen 13/10/2014 19:32
Comment [5]: Biome-averaged values for North America and Russia were changed

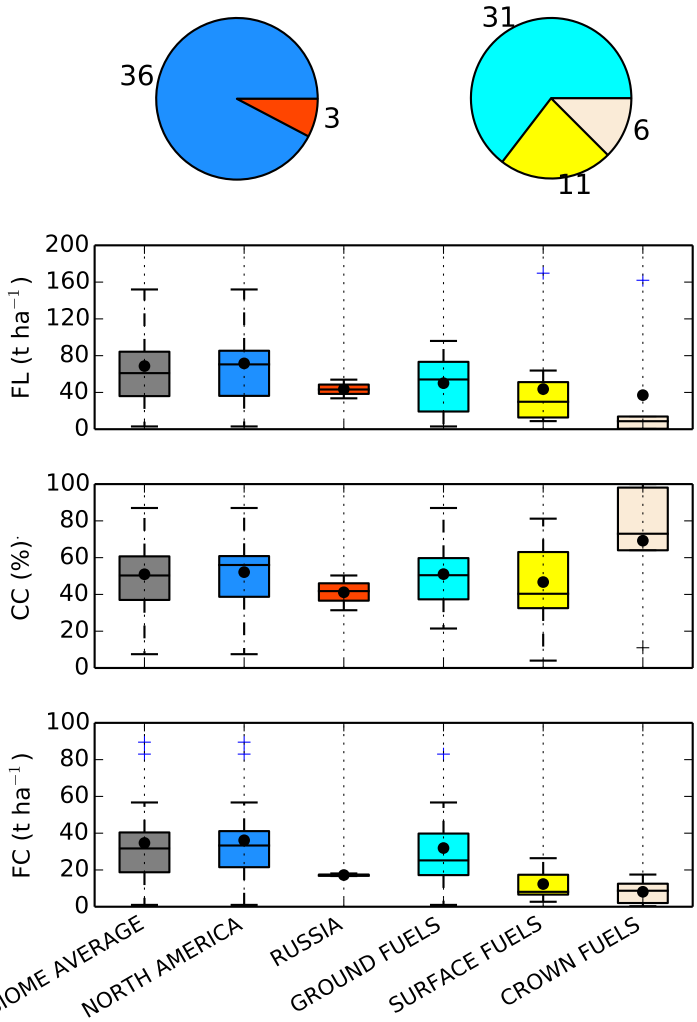
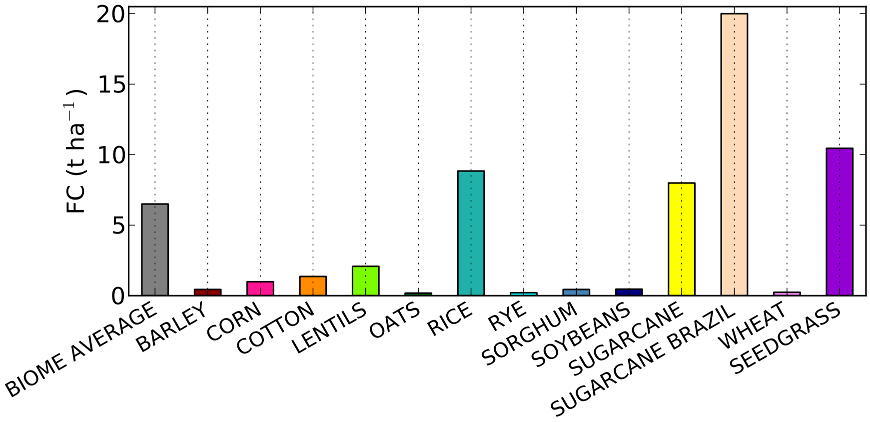


Figure 6: Fuel consumption (FC) for different US crop types as reported by McCarty et al. (2011), and Brazilian sugarcane (Lara et al., 2005). The grey bar corresponds to the biome-averaged FC value for crop residue burning as presented in this study.



Tables

Table 1: Location, fuel load (FL), combustion completeness (CC) and fuel consumption (FC) for field measurements conducted in the savanna (1a), tropical forest (1b), temperate forest (1c), boreal forest (1d), pasture (1e), shifting cultivation (1f), crop residue (1g), chaparral (1h), tropical peat (1i), boreal peat (1j), and tundra biome (1k). Standard deviation (SD) is shown in parenthesis, and values indicated in bold were used to calculate the biome average.

Table 1a: Savanna

Ref[a]	Lat (deg)	Lon (deg)	Location	FL ($t\ ha^{-1}$)	CC (%)	FC ($t\ ha^{-1}$)	Note
1	25.15S	31.14E	Kruger Park, South Africa	**4.4 (1.4)**	**80 (16)**	**3.5 (1.4)**	Lowveld sour bushveld savanna
1	12.35S	30.21E	Kasanka National Park, Zambia	**5.4 (2.1)**	**81 (15)**	**4.2 (1.0)**	Dambo, Miombo, Chitemene
1	16.60S	27.15E	Choma, Zambia	**5.1 (0.4)**	**88 (2)**	**4.5 (-)**	Semi-arid Miombo
2	14.52S	24.49E	Kaoma Local Forest, Zambia	**5.8 (3.8)**	**53 (32)**	**2.2 (1.2)**	Dambo & Miombo
3	15.00S	23.00E	Mongu region, Zambia	**4.2 (0.8)**	**69 (21)**	**2.9 (0.9)**	Dambo & Floodplain
4	12.22N	2.70W	Tiogo state forest, Senegal	**5.8 (1.6)**	**75 (15)**	**4.2 (0.7)**	Grazing & No grazing
5	15.84S	47.95W	Brasilia, Brazil	**8.3 (1.3)**	**88 (13)**	**7.2 (0.9)**	Different types of Cerrado
6	8.56N	67.25W	Calaboza, Venezuela	**6.9 (2.3)**	**82 (17)**	**5.5 (1.9)**	Protected savanna for 27 years
7	15.51S	47.53W	Brasilia, Brazil	**8.3 (-)**	**90 (-)**	**7.5 (-)**	Campo limpo & Campo sujo
8	15.84S	47.95W	Brasilia, Brazil	**8.9 (3.1)**	**92 (4.1)**	**8.2 (2.8)**	Different types of Cerrado
9	3.75N	60.50W	Roraima, Brazil	**6.1 (3.6)**	**56 (27)**	**2.6 (0.9)**	Different types of Cerrado
10	12.40S	132.50E	Kapalga, Kakadu, Australia	**4.8 (1.3)**	**94 (0.6)**	**4.5 (1.3)**	Woodland
11	12.30S	133.00E	Kakadu National Park, Australia	**5.6 (0.9)**	**91 (-)**	**5.1 (-)**	Tropical savanna
12	12.43S	131.49E	Wildman Reserve, Australia	**2.9 (1.8)**	**91 (14)**	**2.4 (1.1)**	Grass & Woody litter
13	12.38S	133.55E	Arnhem plateau, Australia	**3.6 (3.1)**	**44 (35)**	**1.4 (1.6)**	Early & Late season fires
14	12.38S	133.55E	Arnhem plateau, Australia	**8.5 (-)**	**39 (-)**	**4.8 (-)**	Grass & Open Woodland
15	17.65N	81.75E	Kortha Valasa & Kudura, India	**35 (6.4)**	**22 (7.7)**	**7.7 (2.6)**	Woodland

Table 1b: Tropical forest

Ref[a]	Lat (deg)	Lon (deg)	Location	FL ($t\ ha^{-1}$)	CC (%)	FC ($t\ ha^{-1}$)	Note
5	4.30S	49.03W	Marabá, Pará, Brazil	**207 (-)**	**48 (-)**	**103 (-)**	Primary & Secondary forest
16	2.29S	60.09W	Fazenda Dimona, Manaus, Brazil	**265 (-)**	**29 (-)**	**77 (-)**	200 ha clearing for pasture
17	7.98S	38.32W	Serra Talh., Pernambuco, Brazil	**74 (0.2)**	**87 (8.6)**	**64 (6.3)**	Second-growth tropical dry forest
18	4.50S	49.01W	Marabá, Pará, Brazil	**364 (-)**	**52 (-)**	**190 (-)**	Cleared for pastures
18	15.85S	60.52W	Santa Barbara, Rondônia, Brazil	**326 (-)**	**50 (-)**	**166 (-)**	Cleared for shifting cultivation
19	2.61S	60.17W	Manaus, Brazil	**425 (-)**	**25 (-)**	**107 (-)**	Tropical dense rainforest
20	9.11S	63.16W	Jamari, Rondônia, Brazil	**377 (31)**	**50 (4.5)**	**191 (33)**	Primary forest slash
21	2.61S	60.17W	Manaus, Brazil	**402 (-)**	**20 (-)**	**82 (-)**	Humid dense tropical forest
22	10.16S	60.81W	Ariguimes, Rondônia, Brazil	**307 (49)**	**36 (-)**	**110 (-)**	Open tropical forest
23	3.37S	52.62W	Altamira, Pará, Brazil	**263 (-)**	**42 (-)**	**110 (-)**	Lowland Amazonian dense forest
24	2.50S	48.12W	Igarape do vinagre, Pará, Brazil	**214 (-)**	**20 (-)**	**43 (-)**	Tropical dense rainforest
25	5.35S	49.15W	Djair, Pará, Brazil	**121 (17)**	**43 (-)**	**52 (-)**	Slashed Second-growth forest
25	9.20S	60.50W	Rondônia, Brazil	**118 (45)**	**56 (7.7)**	**65 (21)**	Second, Third-growth forest
25	4.30S	49.03W	José, Pará, Brazil	**64 (4.0)**	**87 (-)**	**55 (-)**	Third-growth forest
26	2.34S	60.09W	Fazenda dimona, Manaus, Brazil	**369 (187)**	**30 (-)**	**111 (-)**	Lowland Amazonian dense forest
27	9.52S	56.06W	Alta floresta, Mato Grosso, Brazil	**496 (-)**	**39 (18)**	**192 (87)**	1, 4, and 9 ha clearings
28	9.97S	56.34W	Alta floresta, Mato Grosso, Brazil	**306 (-)**	**24 (-)**	**73 (-)**	Primary forest, 4 ha
29	12.53S	54.88W	Feliz Natal, Mato Grosso, Brazil	**219 (-)**	**71 (-)**	**155 (-)**	Seasonal semi-deciduous forest
30	7.90S	72.44W	Cruzeiro do Sul, Acre, Brazil	**583 (-)**	**39 (-)**	**226 (-)**	Primary forest, 4 ha clearing
31	18.35N	95.05W	Los Tuxtlas, Mexico	**403 (-)**	**95 (-)**	**380 (-)**	Evergreen tropical forest

32	19.30N	105.3W	San Mateo, Jalisco, Mexico	**127 (-)**	**71 (-)**	**91 (-)**	Tropical dry forest
33	0.52S	117.01E	East-Kalimantan, Indonesia	**237 (106)**	**56 (24)**	**120 (47)**	Lightly & Heavily disturbed stands

Table 1c: Temperate forest

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
34	34.80N	82.60W	Southern Appalachians, USA	**110 (-)**	**59 (-)**	**65 (-)**	Mixed pine hardwoods
34	35.21N	83.48W	Nantahala, N. Carolina, USA	**177 (49)**	**52 (5.5)**	**93 (34)**	Pine: Jacob W&E, Devil Den
34	36.00S	79.10W	Hillsborough, N. Carolina, USA	**21 (1.2)**	**11 (-)**	**2.3 (-)**	Loblolly pine forest floor
34	34.80N	82.60W	South East Piedmont, USA	-	-	**5.2 (-)**	Pinus Taeda plantation, forest floor
34	37.50N	122.00W	South East Coastal plain, USA	-	-	**15 (9.1)**	Pine forest floor
35	34.82N	94.13W	Scott County, Arkansas, USA	**10 (-)**	**45 (-)**	**4.7 (-)**	Shortleaf pine-grassland
36	36.60N	118.81W	Sequoia National Park, USA	**231 (-)**	**92 (-)**	**212 (-)**	Mixed conifer trees
37	38.90N	120.67W	Dark Canyon Creek, USA	**141 (49)**	**79 (-)**	**111 (-)**	Two week post-fire
38	38.90N	120.62W	Blodgett Forest, California, USA	**154 (-)**	**70 (-)**	**108 (-)**	Mixed conifer: Moist & Dry burn
39	24.73N	81.40W	National Key Deer Refuge, USA	**23 (5.9)**	**57 (11)**	**13 (4.3)**	Pine forest, Potential fuels
40	42.40N	124.10W	Southwest Oregon, USA	-	-	**39 (-)**	Mixed conifer forest
41	33.56N	81.70W	Savannah River, USA	**19 (-)**	**55 (-)**	**11 (-)**	Mature loblolly, old longleaf pine
42	34.63N	77.40W	Camp Lejeune, N. Carolina, USA	**11 (3.8)**	**45 (29)**	**5.6 (4.7)**	Pine Understory
42	34.01N	80.72W	Fort Jackson, S. Carolina, USA	**10 (-)**	**54 (-)**	**6.3 (2.0)**	Pine Understory
34	36.00S	148.00E	South-East Australia	**79 (-)**	**84 (-)**	**67 (-)**	27 year old Pine plantation
43	33.68S	116.25E	Wilga, Australia	**48 (-)**	**76 (-)**	**28 (-)**	Eucalypt forest
43	34.20S	116.34E	Quillben, Australia	**183 (-)**	**46 (-)**	**58 (-)**	Eucalypt forest
43	33.91S	116.16E	Hester, Australia	**101 (-)**	**68 (-)**	**53 (-)**	Eucalypt forest
43	37.09S	145.08E	Tallarook, Victoria, Australia	**60 (-)**	**61 (-)**	**27 (-)**	Eucalypt forest
43	33.93S	115.46E	McCorkhill, Australia	**70 (-)**	**78 (-)**	**43 (-)**	Eucalypt forest
43	43.22S	146.54E	Warra, Tasmania	**644 (-)**	**62 (-)**	**299 (-)**	Eucalypt forest
43	35.77S	148.03E	Tumbarumba, Australia	**99 (-)**	**70 (-)**	**47 (-)**	Eucalypt forest
44	19.50N	99.50W	Mexico City, Mexico	-	-	**17 (12)**	Pine-dominated forest

Table 1d: Boreal forest

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
45	46.98N	83.43W	Aubinadong River, ON, Canada	**99 (4.2)**	**66 (5.4)**	**34 (6.6)**	Different depth classes used
46	46.78N	83.33W	Sharpsand Creek, ON, Canada	**48 (10)**	**49 (18)**	**23 (7.6)**	Immature jack pine
47	48.92N	85.29W	Kenshoe Lake, ON, Canada	**332 (-)**	**7.5 (-)**	**24 (-)**	Surface & Crown
48	63.38N	158.25W	Innoko, Alaska, USA	-	-	**37 (7.0)**	Black spruce forest/shrub/bog
49	64.45N	148.05W	Rosie Creek, Alaska, USA	-	-	**83**	Ground fuels
49	60.43N	149.17W	Granite Creek, Alaska, USA	-	-	**30**	Ground fuels
49	67.14N	150.18W	Porcupine, Alaska, USA	-	-	**25**	Ground fuels
49	63.12N	143.59W	Tok River, Alaska, USA	-	-	**51**	Ground fuels
49	63.45N	145.12W	Dry Creek, Alaska, USA	-	-	**41**	Ground fuels
49	63.08N	142.30W	Tetlin, Alaska, USA	-	-	**56**	Ground fuels
49	63.50N	145.15W	Hajdukovich Creek, Alaska, USA	-	-	**129**	Ground fuels
50	61.60N	117.20W	Fort Providence, NT, Canada	**83 (10)**	**44 (7.6)**	**36 (5.8)**	Jack pine & black spruce
51	65.10N	147.30W	Alaska, USA	-	-	**19 (1.7)**	Forest floor
52	64.40N	145.74W	Delta Junction, Alaska, USA	**75 (-)**	**48 (-)**	**35 (-)**	Ground fuels: (non)-permafrost
53	53.92N	105.70W	Montreal Lake, SK, Canada	**43 (4.0)**	**62 (7.7)**	**27 (3.9)**	Spruce, Pine, Mixed wood
54	65.03N	147.85W	Fairbanks, Alaska, USA	**95 (17)**	**61 (17)**	**57 (19)**	Different facing slopes
55	46.87N	83.33W	Sharpsand Creek, ON, Canada	**13 (2.0)**	**69 (32)**	**9 (4.0)**	Experimental fire: forest floor
55	48.87N	85.28W	Kenshoe Lake, ON, Canada	**17 (3.0)**	**35 (13)**	**6 (2.0)**	Experimental fire: forest floor
55	61.37N	117.63W	Fort Providence, NT, Canada	**47 (9.0)**	**36 (9.0)**	**17 (3.0)**	Experimental fire: forest floor
55	61.69N	107.94W	Porter Lake, NT, Canada	**15 (0.0)**	**60 (20)**	**9 (3.0)**	Experimental fire: forest floor

55	55.07N	114.03W	Hondo, AB, Canada	**3 (1.0)**	**33 (35)**	**1 (1.0)**	Experimental fire: forest floor
55	59.31N	111.02W	Darwin Lake, NT, Canada	**18 (3)**	**72 (20)**	**13 (3.0)**	Experimental fire: forest floor
55	55.74N	97.91W	Burntwood River, MB, Canada	**72 (12)**	**26 (8.0)**	**19 (5.0)**	Wildfire: forest floor
55	54.29N	107.78W	Green Lake, SK, Canada	**36 (13)**	**86 (54)**	**31 (16)**	Wildfire: forest floor
55	53.57N	88.62W	Kasabonika, ON, Canada	**69 (19)**	**55 (46)**	**38 (30)**	Wildfire: forest floor
55	55.74N	97.85W	Thompson, MB, Canada	**23 (14)**	**87 (63)**	**20 (8.0)**	Wildfire: forest floor
55	54.05N	105.81W	Montreal Lake, SK, Canada	**61 (41)**	**57 (47)**	**35 (17)**	Wildfire: forest floor
55	64.06N	139.43W	Dawson City, YT, Canada	**84 (30)**	**46 (31)**	**39 (22)**	Wildfire: forest floor
55	59.40N	113.03W	Wood Buffalo Nat. Pk., Canada	**37 (9.0)**	**59 (35)**	**22 (12)**	Wildfire: forest floor
56	60.49N	150.98W	Soldotna, Alaska, USA	**91 (22)**	**37 (5.2)**	**33 (4.4)**	Mystery creek 1-3
56	61.61N	149.04W	Palmer, Alaska, USA	**84 (4.2)**	**61 (3.5)**	**51 (5.7)**	Deshka 1-2
56	62.69N	141.77W	Tetlin Refuge, Alaska, USA	**105 (16)**	**45 (15)**	**49 (20)**	Tetlin, Chisana 1-4
56	64.87N	147.71W	Fairbanks, Alaska, USA	**86 (17)**	**37 (22)**	**32 (22)**	Bonanza Creek, Frostfire
57	63.00N	142.00W	Alaska, USA	**152 (-)**	**59 (-)**	**90 (-)**	Black spruce forest
58	65.00N	146.00W	Alaska, USA	**72 (-)**	**58 (-)**	**40 (-)**	Black spruce forest
59	60.45N	89.25E	Bor, Krasnoyarsk, Russia	**34 (-)**	**50 (-)**	**17 (-)**	Pine-lichen forest & litter
60	58.58N	98.92E	Lower Angara, Russia	**54 (12)**	**31 (15)**	**17 (8.6)**	Scots pine, Larch mixed-wood
60	58.70N	98.42E	Lower Angara, Russia	**43 (-)**	**42 (-)**	**18 (-)**	Scots pine, Larch mixed-wood

Table 1e: Pasture

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
20	9.17S	63.18W	Jamari, Rondônia, Brazil	**66 (13)**	**31 (10)**	**21 (17)**	12-year old pasture site
61	5.30S	49.15W	Fransico, Pará, Brazil	**53 (4.8)**	**83 (-)**	**44 (-)**	2 slash fires prior to burning
61	9.20S	60.50W	João & Durval, Rondônia, Brazil	**96 (-)**	**34 (-)**	**30 (-)**	4-year old pasture site
62	2.54N	61.28W	Vila de Apiau, Roraíma, Brazil	**119 (-)**	**20 (-)**	**24 (-)**	Pasture and Forest
32	19.30N	105.3W	San Mateo, Jalisco, Mexico	**35 (-)**	**69 (-)**	**23 (-)**	High & Low severity

Table 1f: Shifting cultivation

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
63	10.53S	31.14E	Kasama, Zambia	**75 (-)**	**64 (-)**	**43 (-)**	Shifting cultivation
64	17.59N	81.55E	Damanapalli & Velegapalli, India	**14 (-)**	**30 (-)**	**4 (-)**	Shifting cultivation in Dry forest

Table 1g: Crop residue

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
65	40.00N	2.00W	Spain, Europe	**1.4 (-)**	**80 (-)**	**1.1 (-)**	Cereal crops
66	22.85S	47.60W	Piracicaba, Sao Paulo, Brazil	-	-	**20 (-)**	Sugar cane
67	33.94N	118.33E	Suqian, China	**6.7 (1.2)**	**44 (4.6)**	**2.9 (0.5)**	Mix (wheat, rice, corn, potato)
68	40.00N	98.00E	North America	**2.4 (3.6)**	**86 (6.0)**	**2.1 (3.2)**	Mix of crop types
68	46.73N	117.18E	North America	**12 (-)**	**90 (-)**	**11 (-)**	Seedgrass

Table 1h: Chaparral

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
69	34.10N	117.47W	Lodi Canyon, California, USA	-	-	**45 (-)**	Prescribed chaparral fire
70	33.33N	117.16W	Bear Creek, California, USA	**60 (5.9)**	**83 (6.0)**	**50 (8.4)**	Mature caenothus & Chamise
70	34.29N	118.33W	Newhall, California, USA	**20 (6.7)**	**75 (4.0)**	**15 (5.4)**	Mature chamise
70	32.32N	117.15W	TNC, California, USA	**21 (-)**	**77 (-)**	**16 (-)**	Young & Healthy chamise
42	34.73N	120.57W	Vandenberg, California, USA	**14 (-)**	**68 (-)**	**10 (-)**	Coastal sage & Maritime chaparral

Table 1i: Tropical peat

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
71	2.52S	113.79E	Kalimantan, Indonesia	-	-	**500 (-)**	Peat & Overstory
72	2.50S	114.17E	Palangka Raya, Indonesia	**399 (11)**	**27 (4.7)**	**109 (19)**	Peat & Overstory
73	2.37S	102.68E	Pelawan, Riau, Indonesia	45 (6.1)	81 (10)	37 (8.2)	Litter & Branches
74	2.52S	113.79E	Kalimantan, Indonesia	-	-	**332 (6.4)**	Peat & Overstory

Table 1j: Boreal peat

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
75	55.85N	107.67W	Patuanak, Canada	-	-	**42 (25)**	Continental & Permafrost bogs
76	54.93N	114.17W	Chisholm, Canada	-	-	**43 (-)**	Hummocks & hollows

Table 1k: Tundra

Ref[a]	Lat (deg)	Lon (deg)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
77	68.58N	149.72W	Anaktuvuk River, Alaska, USA	**165 (15)**	**24 (5.0)**	**40 (9.0)**	Soil & Plants

[a] References: (1) Shea et al., 1996 / Ward et al., 1996; (2) Hoffa et al., 1999; (3) Hély et al., 2003b; (4) Savadogo et al., 2007; (5) Ward et al., 1992; (6) Bilbao and Medina, 1996; (7) Miranda et al., 1996; (8) De Castro and Kauffman, 1998; (9) Barbosa and Fearnside, 2005; (10) Cook et al., 1994; (11) Hurst et al., 1994; (12) Rossiter-Rachor et al., 2007; (13) Russell-Smith et al., 2009; (14) Meyer et al., 2012; (15) Prasad et al., 2001; (16) Fearnside et al., 1993; (17) Kauffman et al., 1993; (18) Kauffman et al., 1995; (19) Carvalho et al., 1995; (20) Guild et al., 1998; (21) Carvalho et al., 1998; (22) Graça et al., 1999; (23) Fearnside et al., 1999; (24) Araújo et al., 1999; (25) Hughes et al., 2000a; (26) Fearnside et al., 2001; (27) Carvalho et al., 2001; (28) Christian et al., 2007 / Soares Neto et al., 2009; (29) Righi et al., 2009; (30) Carvalho et al., 2011.; (31) Hughes et al., 2000b; (32) Kauffman et al., 2003; (33) Toma et al., 2005; (34) Carter et al., 2004; (35) Sparks et al., 2002; (36) Stephens and Finney, 2002; (37) Bêche et al., 2005; (38) Hille and Stephens, 2005; (39) Sah et al., 2006; (40) Campbell et al., 2007; (41) Goodrick et al., 2010; (42) Yokelson et al., 2013; (43) Hollis et al., 2010; (44) Yokelson et al., 2007b; (45) Stocks et al., 1987a; (46) Stocks et al., 1987b; (47) Stocks, 1989; (48) Goode et al., 2000; (49) Kasischke et al., 2000; (50) Stocks et al., 2004; (51) Harden et al., 2004; (52) Harden et al., 2006; (53) de Groot et al., 2007; (54) Kane et al., 2007; (55) de Groot et al., 2009; (56) Ottmar and Sandberg, 2010; (57) Turetsky et al., 2011; (58) Boby et al., 2010; (59) FIRESCAN Science Team, 1996; (60) Ivanova et al., 2011; (61) Kauffman et al., 1998; (62) Barbosa and Fearnside, 1996; (63) Stromgaard, 1985; (64) Prasad et al., 2000; (65) Zarate et al., 2005; (66) Lara et al., 2005; (67) Yang et al., 2008 ; (68) McCarty et al., 2011; (69) Cofer III et al., 1988; (70) Hardy et al., 1996; (71) Page et al., 2002; (72) Usup et al., 2004; (73) Saharjo and Nurhayati, 2006; (74) Ballhorn et al., 2009; (75) Turetsky and Wieder, 2001; (76) Benscoter and Wieder, 2003; (77) Mack et al., 2011.

Table 2: Fuel load (FL), combustion completeness (CC) and fuel consumption (FC) field measurements for different fuel categories within the savanna (2a), tropical forest (2b), temperate forest (2c), and boreal forest biome (2d). Standard deviation (SD) is shown in parenthesis.

Table 2a: Savanna

Cl[a]	Fuel category	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	References[b]
S	Dicots	0.4 (0.5)	91 (12)	0.3 (0.3)	1, 2, 5
S	Grass-dormant	1.9 (1.4)	93 (14)	1.3 (0.5)	1, 2, 5
C	Grass-green	0.4 (0.2)	88 (23)	0.3 (0.1)	1, 2, 5
S	Litter	2.1 (0.5)	88 (13)	1.9 (0.5)	1, 2, 5, 8, 12, 15
S	Tree/shrub leaves	0.4 (0.8)	64 (12)	0.3 (0.6)	1, 2, 5
S	Woody debris (0-0.64cm)	0.6 (0.7)	65 (16)	0.4 (0.5)	1, 2, 5, 8
S	Woody debris (0.64-2.54cm)	0.9 (1.0)	39 (25)	0.5 (0.7)	1, 2, 5, 8
S	Woody debris (>2.54cm)	1.0 (1.1)	21 (12)	0.3 (0.3)	1, 2, 5, 8

Table 2b: Tropical forest

Cl[a]	Fuel category	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	References[b]
C	Attached foliage	3.8 (3.0)	94 (5.1)	3.6 (2.8)	5, 18, 20, 25, 32
S	Dicots	0.5 (0.3)	89 (23)	0.5 (0.3)	5, 18, 20, 25, 32
S	Leaves	13 (8.8)	73 (38)	11 (9.8)	16, 17, 19, 21, 24, 27, 28, 29
S	Litter	18 (9.9)	85 (30)	14 (8.4)	5, 17-29, 32
S	Liana	5.2 (0.8)	21 (35)	0.9 (1.4)	19, 21, 24
G	Rootmat	5.2 (2.7)	87 (13)	4.4 (2.2)	18, 20, 25
S	Woody debris (0-0.64cm)	4.6 (2.8)	94 (4.8)	6.4 (8.6)	5, 17, 18, 20, 25, 32
S	Woody debris (0.65-2.54cm)	17 (3.9)	87 (7.9)	15 (4.0)	5, 17, 18, 20, 25, 32
S	Woody debris (2.55-7.6cm)	27 (15)	65 (19)	18 (13)	5, 17, 18, 20, 25, 32
S	Woody debris (7.6-20.5cm)	45 (29)	41 (18)	18 (9.3)	5, 17, 18, 20, 25, 32
S	Woody debris (>20.5cm), Trunks	147 (83)	32 (23)	37 (32)	5, 16, 18-23, 26-30

Table 2c: Temperate forest

Cl[a]	Fuel category	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	References[b]
G	Organic Soil	58 (40)	60 (44)	25 (31)	34, 37, 38
S	Litter	20 (11)	81 (8.9)	17 (9.9)	34, 37, 38
S	Woody debris (0-0.64cm)	1.2 (0.8)	87 (11)	1.0 (0.6)	36, 37, 38
S	Woody debris (0.65-2.54cm)	5.2 (1.9)	79 (11)	4.0 (1.2)	36, 37, 38
S	Woody debris (2.55-7.6cm)	6.0 (0.9)	73 (14)	4.3 (0.2)	36, 37, 38
S	Woody debris (7.6-20.5cm sound)	16 (9.6)	38 (42)	6.2 (8.2)	36, 37, 38
G	Woody debris (7.6-20.5cm rotten)	20 (4.1)	96 (5.4)	20 (4.8)	36, 37, 38

Table 2d: Boreal forest

Cl[a]	Fuel category	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	References[b]
G	Ground fuels (Soil, Forest floor)	50 (29)	51 (18)	32 (26)	44, 48, 49, 50, 51, 53, 54, 55, 57, 58
S	Surface fuels	44 (49)	52 (25)	12 (8.1)	44, 46, 49, 52, 55, 58, 59
C	Crown fuels	37 (70)	71 (29)	8.1 (6.9)	44, 46, 49, 57, 59

[a] Fuel category classification: S = Surface fuels, G = Ground fuels, C = Crown fuels

[b] References: (1) Shea et al., 1996 / Ward et al., 1996; (2) Hoffa et al., 1999; (5) Ward et al., 1992; (8) De Castro and Kauffman, 1998; (12) Rossiter-Rachor et al., 2007; (15) Prasad et al., 2001; (16) Fearnside et al., 1993; (17) Kauffman et al., 1993; (18) Kauffman et al., 1995; (19) Carvalho et al., 1995; (20) Guild et al., 1998; (21) Carvalho et al., 1998; (22) Graça et al., 1999; (23) Fearnside et al., 1999; (24) Araújo et al., 1999; (25) Hughes et al., 2000a; (26) Fearnside et al., 2001; (27) Carvalho et al., 2001; (28) Christian et al., 2007 / Soares Neto et al., 2009; (29) Righi et al., 2009; (30) Carvalho et al., 2011.; (32) Kauffman et al., 2003; (34) Carter et al., 2004; (36) Stephens and Finney, 2002; (37)

Bêche et al., 2005; (38) Hille and Stephens, 2005; (45) Stocks et al., 1987a; (47) Stocks, 1989; (49) Kasischke et al., 2000; (50) Stocks et al., 2004; (51) Harden et al., 2004; (52) Harden et al., 2006; (53) de Groot et al., 2007; (54) Kane et al., 2007; (55) de Groot et al., 2009; (56) Ottmar and Sandberg, 2010; (58) Boby et al., 2010; (59) FIRESCAN Science Team, 1996; (60) Ivanova et al., 2011;

Table 3: Biome-averaged values for fuel load (FL), combustion completeness (CC), and fuel consumption (FC) field measurements. Column 5 shows the FC per unit burned area as used in GFED3 (FC_{GFED3}) and in column 6 the difference (%) of FC_{GFED3} compared to the average FC of field measurements is given. Standard deviation (SD) is shown in parenthesis.

Biome	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})[a]	FC_{GFED3} (t ha^{-1})[b]	Difference (%)[c]
Savanna	7.6 (6.5)	71 (26)	4.6 (2.2)	7.9	+72
Grassland Savanna	5.3 (2.0)	81 (16)	4.3 (2.2)	7.7	+78
Wooded Savanna	11 (9.1)	58 (32)	5.1 (2.2)	8.1	+59
Tropical Forest	285 (137)	49 (22)	126 (77)	215	+71
Temperate Forest	115 (144)	61 (18)	58 (72)	15	-74
Boreal Forest	69 (61)	51 (17)	35 (24)	62	+79
Pasture	74 (34)	47 (27)	28 (9.3)	168	+491
Shifting Cultivation	44 (-)	47 (-)	23 (-)	6.5	-72
Crop Residue	8.3 (9.9)[d]	75 (21)	6.5 (9.0)	5.6	-13
Chaparral	34 (23)[e]	76 (6.2)	27 (19)	3.5	-87
Tropical Peatland	1056 (876)[f]	27 (-)	314 (196)	228	-27
Boreal Peatland	-	-	42 (-)	25	-40
Tundra[g]	165 (15)	24 (5.0)	40 (-)	-	-

[a] For biomes where only one or two measurements are available, no uncertainty estimate is given.

[b] FC per unit area burned according to GFED3, averaged over 1997-2009. The number represents the FC rate for the collocated grid cells, i.e. grid cells in which field measurement were taken. Note that for this calculation the assumption was made that GFED burned area is equally divided over different fire types in one grid cell, which may influence average FC_{GFED3} values.

[c] FC_{GFED3} compared to the average FC of field measurements for collocated grid cells. Positive numbers indicate that FC_{GFED3} is higher than the average FC of field measurements.

[d] We assumed an average CC of 88% as reported in McCarty et al. (2011) to estimate FL for the study of Lara et al. (2005).

[e] We assumed a CC of 76% (average CC for studies of Hardy et al. (1996) and Yokelson et al. (2013)) to estimate FL for the study of Cofer III et al. (1988).

[f] We assumed an average CC of 27.2% as reported in Usup et al. (2004) to estimate FL for studies of Page et al. (2002) and Ballhorn et al. (2009).

[g] For the measurement location in the tundra biome no area burned was detected by GFED, and therefore no comparison with GFED3 estimates was made.

Letter to editor

Rio de Janeiro, 13/10/2014

Dear editor of ACP,

We greatly appreciate the constructive reviews and editor assessments of our paper. Based on the reviewers' comments we modified the text and expanded the database by including several new interesting studies. More specifically, the following main concerns of the reviewers were addressed:

- The level of scientific focus was increased by providing uncertainties (either standard deviation or range, depending on the number of studies available) throughout the text for the different FL, CC and FC values.
- Terminology like 'fuel loading' and 'ground fuels' are now more clearly defined and used more consistently throughout the paper. The same counts for the definition of the different biomes: for example, we used a fraction tree cover map now to distinguish between wooded savanna and tropical dry forest.
- Within the temperate and boreal forest biomes we expanded the discussion on differences in wildfire and prescribed fire fuel consumption. Moreover, new biome-averaged values for both biomes are presented.
- We introduced a new 'shifting cultivation' section, and removed these measurements from the pasture section.

Please find a detailed response below.

Kind regards,

Thijs van Leeuwen, on behalf of all co-authors

Response to referee #1 (R. Yokelson)

General comments:

This can be a useful database for the scientific community with a bit more work. The authors could highlight in the abstract, or elsewhere sooner in paper, that this is an updateable database that resides on the Internet.

We highlight in the Introduction Section that the database will be updated frequently and is available online, by adding the following sentence:

P6L16-17: "The database, available at http://www.globalfiredata.org/FC, will be updated when new information becomes available."

In addition, this message was repeated in the Summary Section:

P30L23-25: "When new information on fuel consumption becomes available, the field measurement database will be updated. The most up-to-date version can be retrieved from http://www.globalfiredata.org/FC."

A few methodological notes. In much of the refereed literature "fuel loading" is considered equivalent to "total biomass." In US land management agencies, and some refereed literature, "fuel" has a very different operational definition meaning the biomass expected to experience significant consumption under the current weather and fuel moisture conditions. It's not uncommon then to calculate fuel loading (FL) as e.g. "biomass less than 2.5 cm in diameter and less than one meter above ground." The authors allude to possibly using the more restrictive operational definition on page 4 line 14. It's important to distinguish because if one applies a combustion completeness (CC) calculated with respect to a restrictive pre-fire fuel loading to total biomass, the overall biomass burned or "fuel consumption" (FC) can be too high. The authors should ensure they do not fall in that trap.

It is indeed important to distinguish between these different definitions, because the calculated combustion completeness with respect to total biomass or the more restrictive fuel load will impact the fuel consumption estimates.

In the database presented we only allude to a more restrictive operational definition when authors of a refereed study did so, and in some of these studies a 'total available biomass' is not even presented. To make clear that in most of the literature consulted the 'fuel load' was actually equivalent to 'total available biomass', we changed the following text in the Introduction Section:

P4L22-29: "In general, the FL is equivalent to the total biomass available. New studies do provide estimates of standing biomass (e.g. Baccini et al., 2012). However, fires do not necessarily affect standing biomass. Especially in savannas the trees are usually protected from burning by a thick barch and in some of the literature the FL therefore has a more restrictive definition, referring to only that portion of the total available biomass that normally burns under specified fire conditions, which is often only the fine ground fuels. In both definitions the FL is typically expressed as the mass of fuel per unit area on a dry weight basis."

Moreover, we expanded the discussion in Section 3.2 by making clear that this fuel load definition issue will add uncertainty and may impact the FC:

P25L33-P26L4: "Note that for temperate and boreal forest measurements sometimes the more restrictive definition of FL (as presented in Section 1) was used, and this can have an impact on FC values as well; if one applies a CC calculated with respect to a restrictive pre-fire FL to total biomass available, the overall FC that was estimated can be too high."

Also, the temperate forest and chaparral ecosystem-average FC values seem too high and some effort should be made to distinguish wild and prescribed fire FC at least for the temperate forest ecosystem as explained in more detail below. Section 3.7 and Table 5 of this open-access paper provides some prescribed fire FL and FC measurements the authors may want to include: http://www.atmos-chem-phys.net/13/89/2013/acp-13-89-2013.html

As noted by the reviewer, fuel consumption of wildfires is higher than in prescribed fires according to conventional wisdom and also according to the data presented in Tables 1 of our paper. We agree that these differences between wildfires and prescribed burns are too large to neglect, and therefore we made the following changes:

* We expanded Section 2 on the measurements, by stating that –in general- obtaining FC measurements for wildfires is more challenging than for prescribed burns:
P7L12-21: "Most of the studies we found in the literature rely on the planar intersect method (PIM), where fuel measurement plots are typically divided in multiple, randomized smaller subplots. The (small-size) biomass in these subplots is oven dried and weighed both pre- and post-fire to estimate the CC and to determine the FC. The consumption of larger-size material (diameter >10cm) is often estimated based on experimental observations of randomly selected trunks and branches that were identified before the fire (Araújo et al., 1999). The PIM is mainly applied in prescribed burns, and obtaining FC measurements for large wildfires is logistically more challenging but can be based on comparing burned with adjacent unburned patches."

* Within the temperate forest biome we now distinguish between wildfires and prescribed burns:
P12L32-P13L7: "While tropical fires are largely intentionally ignited to pursue land management goals, the temperate forest is also subject to wildfires. Obtaining FC measurements for wildfires is obviously challenging, so most information is derived from prescribed fires which allow researchers to measure pre-fire conditions. However, these fires may not always be a good proxy for wildfires. For example, wildfires in western conifer forest of the US are often crown fires (while prescribed fires usually only burn surface fuels). Due to potential discrepancies with respect to FC, we distinguished between these fire types in Section 3.2."

* Several prescribed fire FL and FC measurements from the study of Yokelson et al. (2013) were included, as presented in Table 1c.

* We calculated the biome-averaged values for the temperate forest biome in a different way: instead of focusing on 'total FC' studies, we now use all measurements presented in Table 1c. Thus, studies that provide information on one specific fuel class only (e.g. ground fuels (Goodrick et al., 2010)) were also included. Due to this, the calculated biome-averaged FC for the temperate forest biome decreased from 93 ± 79 t ha^{-1} to 58 ± 72 t ha^{-1}, and is now closer to what we expect.

* We expanded the discussion on differences between wildfires and prescribed fires in Section 3.2, and provide the reader with FC values that may be more representative for both fire types:

P25L15-P26L4: "In the temperate forest biome FC was underestimated in GFED3 by 74% compared to the field measurement average for collocated grid cells. In our averaged field measurement estimate we included all measurements presented in Table 1c. As noticed in Section 2.3, it is likely though that studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels) are more representative for wildfires. Prescribed burns, on the other hand, tend to burn less fuel and therefore the studies that only include ground or surface fuels were probably more representative for this fire type. When focusing on studies that provide information on one specific fuel class only, the field average for the temperate forest would be significantly lower (13±12 t ha^{-1}) as well as the discrepancy with GFED3 (+14%). This FC value of 13 t ha^{-1} may be more realistic for prescribed fires, which contribute to roughly 50% of all temperate forest fire emissions in the contiguous United States (CONUS). Still, it remains very uncertain how well FC measured for specific fuel classes is representative for prescribed fires and wildfires. This issue also counts for boreal forests, where GFED3 overestimated the field measurements by almost 80%. When only including studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels), the field average for the boreal forest would increase from 35±24 t ha^{-1} to 39±19 t ha^{-1} and the discrepancy with GFED3 would decrease (from +79 to +60%). This value of 39±19 t ha^{-1} may be more representative for boreal wildfires. Note that for temperate and boreal forest measurements sometimes the more restrictive definition of FL (as presented in Section 1) was used, and this can have an impact on FC values as well; if one applies a CC calculated with respect to a restrictive pre-fire FL to total biomass available, the overall FC that was estimated can be too high."

* We decided not to label prescribed fires and wildfires in table 1c, since it is not always clear if a study is more representative for one of these fire types. Moreover, the study in Mexico (Yokelson et al., 2007) was actually the only 'real' wildfire that was measured.

* Several chaparral measurements from Yokelson et al. (2013) were included, and lowered the biome-averaged FC from 32±19 t ha^{-1} to 27±19 t ha^{-1} and is now closer to what we expect.

The writing needs to have a sharper, higher-level scientific focus. The statement that readers must use "extreme caution with average values" doesn't meet the normal scientific criteria for expressing the situation nor does omitting the uncertainties. The way to explain it scientifically is that FC is naturally variable and hard to measure and there are few measurements for some ecosystems. Thus confidence in the average value is low and the coefficient of variation is large. It's important therefore to include uncertainties for each value in the text and let the user assess the implications for their application. In general, high uncertainty alone does not justify implementing a non-average value, but using non-average values could be justified if they were produced by a validated model that explains the observed variability in field measurements. If the authors believe such a model exists they should promote it clearly. At present, a comparison is presented towards end of paper, but no conclusion is presented after the comparison. Using a non-average value, but within the uncertainty, could also be of interest (or convenient) if it systematically improves representation of e.g. downwind concentrations. In this latter case, it would ideally be made clear by the user if altering the FC is the only reasonable solution or if a change in other uncertain parameters (e.g. burned area) cannot be ruled out.

Although it is problematic to properly quantify uncertainties, especially given the ‘definition’ problem for ecosystems and/or terms like ‘fuel load’, and limited amount of information for most biomes, we agree that more effort can be put into the scientific explanation and writing. In general, we made the following changes to have a sharper higher-level scientific focus throughout the text:

* Uncertainties for each average value were consistently added. We appended the standard deviation, or range when only two values are available.

* We added a more scientific discussion and conclusion on the use of biome-averaged values:
P26L5-13: “For most biomes, a few field measurements had a FC that was an order of magnitude larger than the other values listed in Table 1, which explains the discrepancy between the median and average FC values that was sometimes found (e.g. the ‘Australia and Tasmania’ region in Figure 4). By neglecting these ‘outliers’ the biome-averaged values may change significantly, but this could lead to erroneously low or high estimates as well. In general, FC shows large variability between biomes, within biomes, and even within a specific fuel type. FC is often hard to measure, and since only a few measurements are available for some biomes, care should be taken when using the biome-averaged values presented in this paper.”

Also, the word “rate” is used erroneously throughout the paper since “rate” implies an amount per time rather than an amount per area.
Agreed and deleted where required.

I believe the authors intent is to offer this a useful database and not a comprehensive treatise on uncertainties in calculations of biomass burned at various scales, but they could provide a slightly broader summary of uncertainty at the top of page 5 by including or recognizing some of the following points: A fire that is missed by FRP may be seen as burn scar, this is a possibility, but not a given fact because many short-lived fires also have small burn scars. In general, detection of fires as heat, fire emissions, and burn scars is far from complete. Challenges for bottom-up or top-down approaches are clouds, the cloud mask, and orbital gaps. Added challenges for bottom up approaches include fires that are too small, canopy obscuration, sites that green up before next look, and detected fires assumed to be in wrong ecotype or uncertainty in FC in general. Additional weaknesses of top-down include uncertainty in injection altitude, meteorology, secondary chemistry, poor spatial and temporal resolution, and the unknown contribution of other sources. All approaches are highly uncertain, but work should continue on all because biomass burning is a very important source.
As noticed by the reviewer, the scope of this paper is to present a useful database and not a comprehensive treatise on uncertainties in calculations of biomass burned at various scales. In our paper we discuss different properties that are used to estimate emissions, and we do provide a short summary of their uncertainty and/or we refer to papers where these uncertainties are discussed in more detail. Examples are given in:

P4L14-19: “The burned area may be estimated directly from satellite observations, with the MODerate resolution Imaging Spectroradiometer (MODIS) 500 m maps (Roy et al., 2005; Giglio et al., 2009) being currently the most commonly used products for large-scale assessments. Although small fires and fires obscured by forest canopies escape detection with this method (Randerson et al. 2012), the extent of most larger fires can be relatively well constrained in this way."

P5L3-13: "Another approach that has been developed over the past decade is the measurement of fire radiative power (FRP) (Wooster et al., 2003; Wooster et al., 2005; Kaiser et al., 2012). FRP per unit area relates directly to the fuel consumption (abbreviated as 'FC' in the remainder of the paper) rate, which again is proportional to the fire emissions. The FRP method has several advantages compared to the Seiler and Crutzen (1980) approach, such as the ability to detect smaller fires and the fact that the fire emissions estimates derived this way do not rely on FL or CC. One disadvantage is that the presence of clouds and smoke can prevent the detection of a fire, and the poor temporal resolution of polar orbiting satellites hampers the detection of fast moving or short-lived fires (which still can show a burn scar in the burned area method) and makes the conversion of FRP to fire radiative energy (FRE, time-integrated FRP) difficult."

However, to emphasize that uncertainties are substantial for the different properties, we added the following text and refer to van der Werf et al. (2010), who provide a more detailed discussion on these uncertainties:
P4L13-14: "These four properties are obtained in different ways and generally uncertainties are substantial (van der Werf et al., 2010)."

The need to assign ecosystems properly to use this data suggests a possible additional short section would be useful with recommendations on vegetation maps/layers or at least citations to commonly used options and/or any review articles on the topic.
Indeed, to use this database the different ecosystems need to be assigned properly, and therefore a clear and consistent definition throughout the paper is key. As suggested by the reviewer we redefined some biomes and provide a more clear description in the different biome sections (2.1-2.11). In general, the following changes were made:

* Within the savanna biome we now distinguish between grassland savannas and wooded savannas, and use these terms consistently throughout the paper.

* Within the tropical forest biome we distinguish between tropical evergreen forest and tropical dry forest. To distinguish between tropical dry forest and wooded savanna, we harmonized with the emission factor compilation of Akagi et al. (2011), in which 60% canopy cover was the delineation:
P12L6-10: "Different forest types may partly explain the discrepancy found, and therefore we distinguished between measurements conducted in primary tropical evergreen forest, secondary tropical evergreen forest, and tropical dry forest (Figure 3). To distinguish between tropical dry forests and wooded savannas (Section 2.1), we harmonized with the emission factor compilation of Akagi et al. (2011) in which 60% canopy cover (Hansen et al., 2003) was the delineation between both ecosystems."

* To distinguish between boreal and temperate forests, we define boreal forest as "high latitudes of about 50-70°" forested regions on P14L10. Within the temperate and boreal forest biome we now distinguish between wildfires and prescribed fires as well.

* Within the pasture biome (section 2.5) we removed the two shifting cultivation studies, which were then included into a new 'shifting cultivation' section (2.7).

Specific Comments:

P8117, L3: first use of "rate" which I suggest to eliminate
"These fuel consumption (FC) rates depend" was changed to "Fuel consumption (FC) depends".

P8118, L8: particles also
We changed "accurate trace gas emission estimates" to "accurate trace gas and particle emission estimates".

P8118, L13: change "can be obtained directly" to "may be estimated" since there are options and it's not an exact measurement.
"can be obtained directly" was changed to "may be estimated".

P8119, L1: here "rate" is OK since power has time in the denominator.
"rate" was not deleted here.

P8119, L10 "emissions" to "consumption"
"emissions" was changed to "consumption".

P8119, L15: append "which is updated on-line"
"The accompanying database is updated frequently and on-line." was appended.

P8119, L17: add "also" after the first "is" since FC is fundamentally the difference between pre and post fire biomass loading. Assuming that FL X CC is as useful is strictly true if FL and CC don't depend on each other.
The sentence was changed to:
P5L22-24: "To improve and validate fire emissions models, it is crucial to gain a better overview of available FC measurements, as well as of the FL and CC components that together govern FC."

P8119, L20: I believe it is fire-integrated FRE (energy) divided by fire-integrated burned area that might give FC under ideal conditions. Getting FC from FRP would be like trying to measure how far a car drove by measuring its speed at one point.
We agree, and to be more specific we changed the text to:
P5L24-27: "This is obviously the case for emissions estimates based on burned area, but also FRP-estimates could benefit from this information because one way to constrain these estimates is dividing the fire-integrated FRE by the fire-integrated burned area, which in principle should equal FC."

P8119, L23-24: I would just say that fine fuels usually have a higher CC than coarse fuels since there a general inverse relationship between FL and CC has not been demonstrated (at least not in this paper, e.g. more grass is not known to make CC decrease?).
Indeed, this inverse relationship between FL and CC has not been clearly demonstrated, and therefore the text was changed to:
P5L30-33: "Forested ecosystems in general show relatively little variability in FL over time for a given location, but CC can vary due to weather conditions. Fine fuels usually burn more complete than coarser fuels, and therefore CC in grassland savannas is often higher than in forested ecosystems."

P8119, L24-25: In the absence of disturbances total forest biomass tends to increase at a well-behaved rate, but depending on how FL is defined it can change with the weather. The authors should choose one definition of FL and use throughout – or clarify that this problem adds uncertainty.

When discussing seasonal variations of FL within the savanna biome, it is indeed important to clearly state how the FL is defined. To make clear that in most of the literature consulted the 'fuel load' was actually equivalent to 'total available biomass', we changed the following text in the Introduction Section:

P4L22-29: "In general, the FL is equivalent to the total biomass available. New studies do provide estimates of standing biomass (e.g. Baccini et al., 2012). However, fires do not necessarily affect standing biomass. Especially in savannas the trees are usually protected from burning by a thick barch and in some of the literature the FL therefore has a more restrictive definition, referring to only that portion of the total available biomass that normally burns under specified fire conditions, which is often only the fine ground fuels. In both definitions the FL is typically expressed as the mass of fuel per unit area on a dry weight basis."

Moreover, we expanded the Discussion Section 3.2 by making clear that this fuel load definition issue will add uncertainty and may impact the FC:

P25L33-P26L4: "Note that for temperate and boreal forest measurements sometimes the more restrictive definition of FL (as presented in Section 1) was used, and this can have an impact on FC values as well; if one applies a CC calculated with respect to a restrictive pre-fire FL to total biomass available, the overall FC that was estimated can be too high."

P8120, L9: Akagi et al listed 47 FC measurements for nine fuel types to provide examples, this paper is a first attempt at a comprehensive tabulation of refereed measurements.

We changed the text and now refer to the useful work of Akagi et al. (2011):

P6L12-15: "Building on Akagi et al. (2011), who listed 47 measurements for nine fuel types, this paper is a first attempt to establish a complete database, listing all the available FC field measurements for the different biomes that were found in the peer-reviewed literature".

P8121, L11: "After the burn" implies a prescribed fire or slowly moving wildfire and comparisons in and out of fire perimeter are also done post fire.

Several changes were made to the description of the planar intersect method, and its acronym (PIM) is now used throughout the remainder of our manuscript:

P7L12-21: "Most of the studies we found in the literature rely on the planar intersect method (PIM), where fuel measurement plots are typically divided in multiple, randomized smaller subplots. The (small-size) biomass in these subplots is oven dried and weighed both pre- and post-fire to estimate the CC and to determine the FC. The consumption of larger-size material (diameter >10cm) is often estimated based on experimental observations of randomly selected trunks and branches that were identified before the fire (Araújo et al., 1999). The PIM is mainly applied in prescribed burns, and obtaining FC measurements for large wildfires is logistically more challenging but can be based on comparing burned with adjacent unburned patches."

P8122, L5: is Mg ha-1 actually better? If using metric tons they are sometimes *spelled "tonnes" to avoid confusion with British "ton" – either way it should be plural!*

We decided to stick to the tons ha-1, and therefore changed "ton" to "tons" instead.

P8122, L16&17: Reminder, improper uses of the word "rate"

The word "rate" was removed here.

P8123, L3: using "dry savanna" before defining, fix suggested next comment

P8123, L5-7: suggest moving these two sentences after the Gill and Lana reference on previous page.

We followed the suggestion and moved the two sentences after the Gill and Allan (2008) reference.

P8123, L4-5: Note I backed up. For grass production to limit area burned maybe it needs to be explained that fuel density can affect how well a fire propagates for a given wind speed?

We added a more detailed explanation by changing the text to:

P9L8-14: "As these systems are generally fuel limited, grass production and consumption by herbivores are very important factors controlling the extent of area burned particularly in drier regions where rainfall can vary strongly between years (Menaut et al., 1991; Cheney and Sullivan, 1997; Russell-Smith et al. 2007). Grass production controls fire spread because low-biomass grasslands have less continuous fuel swards, and also because they burn at lower intensities which reduces the probability of spread".

P8123, L12-13: the lack of grasses that "restrict" nitrification causing moisture-independent low biomass in Australia. Can this be restated so it is more obvious what is meant?

We restated this sentence to:

P9L19-21: "This difference is mostly due to the fact that Australia's native grasses are limited by nitrogen availability at high rainfalls, something African grasses such as *Andropogon gayanus* overcome through various mechanisms (Rossiter-Rachor et al., 2009)".

P8123, L14: Miombo and Cerrado and "Monsoon" Forest are also commonly called "tropical dry forest," maybe more often than a savanna? This is an important "gray area" that could be pointed out. In Akagi et al 2011 they adopted a percent tree cover value as an unambiguous threshold. Here the authors appear to have adopted yet another term that is seen sometimes: "wooded savanna."

As mentioned by the reviewer, unclear definitions of these different ecosystems may confuse the reader and it is therefore important to point out this gray area. Within the savanna biome we consistently distinguish between grassland savanna and wooded savanna. We harmonized with the emission factor compilation of Akagi et al. (2011), in which 60% canopy cover (fraction tree cover (FTC)) was the delineation between wooded savanna and tropical dry forest. The FTC product was derived from the Vegetation Continuous Fields (VCF) collection which contains proportional estimates for vegetative cover types: woody vegetation, herbaceous vegetation, and bare ground (Hansen et al., 2003). This is stated in the tropical forest section (Section 2.2):

P12L6-10: "Different forest types may partly explain the discrepancy found, and therefore we distinguished between measurements conducted in primary tropical evergreen forest, secondary tropical evergreen forest, and tropical dry forest (Figure 3). To distinguish between tropical dry forests and wooded savannas (Section 2.1), we harmonized with the emission factor compilation of Akagi et al. (2011) in which 60% canopy cover (Hansen et al., 2003) was the delineation between both ecosystems."

P8123, L20: I never heard of "dense woodland" meaning "tropical dry forest" or "open forest" or "wooded savanna."

We removed "dense woodland" and replaced it with "wooded savanna".

P8123, L24: Very important to add the variability here and throughout! I suggest to append standard deviation (or range in the case of only two values) to each average value given as a matter of habit.

As explained in the 4th general comment, we added uncertainties for each average value throughout the text. In principle we append the standard deviation, but when only two values are available we use the range.

P8123, L28&29: not sure regional differences are "substantial" especially compared to uncertainties or natural variation and maybe also add "nominally" before "higher."

We deleted "substantial" and added "nominally" before "higher".

P8124, L4: the "differences" are not statistically significant. "Conclusive findings" is a different concept.

We agree that this is a different concept, and therefore we restated the sentence to: P10L10-11: "A larger number of measurements are required to conclusively say whether these differences are statistically significant."

P8124, L14: "surface area to volume"

"area" was changed to "surface area".

P8124, L23: This or in discussion may be a good place to point out that the analysis of CC data by Akagi et al 2011 (Sect 2.4) suggests that CC increases over the course of the dry season as large diameter fuels dry out. This idea is consistent with a seasonal decrease in MCE proposed by Eck et al. (2013):

We decided to point out these temporal variations of CC (and thus FC) in the discussion (Section 3.1), where we added the following text:
P22L26-29: "In general, both FC and CC may increase over the course of the dry season as large diameter fuels dry out. This was also suggested by Akagi et al. (2011) for the savanna biome, and consistent with a seasonal decrease in MCE as proposed by Eck et al. (2013)."

P8124, L24: I think the more precise terminology is tropical "evergreen" forest? A sentence fragment or some idea on how common droughts are would be helpful since the Amazon has had quite a few droughts in the last few years.

We used the more precise terminology and replaced "Tropical rainforests" with "Tropical evergreen forests".

Moreover, to highlight the importance of droughts in tropical forests, we included some relevant references for Indonesia (Field et al., 2009) and the Amazon (Marengo et al., 2011; Tomasella et al., 2013).

P8125, L7: "tons" to "t" or "Mg." I think you need to better differentiate at the outset between 1) deforestation fires, where as much biomass as possible is cut and piled and the desire is to remove the biomass as completely as possible, often in a series of burns and 2) mostly accidental or escaped fires in selectively logged forests where conversion to agriculture is not a goal. Then discuss the factors affecting these two fire types separately.

"tons" was changed to "t".

Within the tropical forest biome we distinguish between tropical evergreen forest and tropical dry forest. For tropical evergreen forest, we tried to better differentiate between deforestation fires and accidental fires by adding the following text:

P11L1-12: "Human activities have resulted in fire activity in tropical forests, often with the goal to clear biomass and establish pasture or cropland. These deforestation fires can be small-scale (e.g. shifting cultivation, discussed in Section 2.6) or on large scale with the aid of heavy machinery. In the latter case, biomass is often piled in windrows after the first burn and subject to additional fires during the same dry season to remove the biomass more completely. In large-scale deforestation regions like the state of Mato Grosso in the Brazilian Amazon, the expansion of mechanized agriculture could result in increased fuel consumed per unit area (Cardille and Foley, 2003; Yokelson et al., 2007). All these fires, but also selective logging, may lead to more frequent accidental fires as fragmented forests are more vulnerable to fire (Nepstad et al., 1999; Siegert et al., 2001; Pivello, 2011)."

P8125, L20: This is a bit oversimplified: This paper: http://www.atmos-chem-phys.net/7/5175/2007/acp-7-5175-2007.html Sect 2.3.2 gives a more specific discussion of past work by Fearnside, Kauffman, Cochrane, Morton, etc. In general, forest slash that doesn't burn in a first fire may be subjected to additional fires during the same dry season. If conversion to pasture is the goal more residual biomass can be tolerated and it is mostly removed during pasture fires in subsequent years. If conversion to e.g. mechanized soybean production is the goal, the slash (or residual material) is often assembled in windrows (long piles) to enhance CC. Other times crop residue fires or deforestation fires accidentally escape and burn some nearby degraded forest.

We consulted the ACP paper and provided some more detail on the different processes, as presented in the previous comment.

P8126, L3-4: The authors should use more consistent definitions of various ecosystems. Here tropical dry forests are mentioned in the tropical forest section and many people might include Miombo in that. One possibility is to harmonize with the emission factor compilation of Akagi et al 2011 in which 60% canopy cover was the delineation between wooded savanna and tropical dry forest. From page 5 of that paper: "Tropical dry forest is also called "seasonal" or "monsoon" forest. Tropical dry forests (TDF) differ from "woody" savanna regions in that TDF are characterized by a significant (>60%) canopy coverage or closed canopies (Mooney et al., 1995; Friedl et al., 2002). Savanna regions are qualitatively described as grassland with an "open" canopy of trees (if any)."

As suggested by the reviewer we redefined some biomes and provided a more clear description in the different biome sections (2.1-2.11). Regarding the tropical forest

biome: we now harmonized with the emission factor compilation of Akagi et al. (2011) in which canopy cover (fraction tree cover (FTC)) of at least 60% was the delineation between tropical dry forest and wooded savanna. The FTC product was derived from the Vegetation Continuous Fields (VCF) collection which contains proportional estimates for vegetative cover types: woody vegetation, herbaceous vegetation, and bare ground (Hansen et al., 2003).
P12L6-10: "Different forest types may partly explain the discrepancy found, and therefore we distinguished between measurements conducted in primary tropical evergreen forest, secondary tropical evergreen forest, and tropical dry forest (Figure 3). To distinguish between tropical dry forests and wooded savannas (Section 2.1), we harmonized with the emission factor compilation of Akagi et al. (2011) in which 60% canopy cover (Hansen et al., 2003) was the delineation between both ecosystems."

P8126, L8: reminder "FC" ok by itself does not need "rate" to follow it
"rate" was removed.

P8126, L15: The observation of size or class dependent CC goes back to at least Ward et al 1992
We have not included a citation because it is a very general observation.

P8126, L16: "surface area"
"area" was changed to "surface area".

P8126, L22: I suggest that this section be divided into prescribed and wild fires (PF and WF). Otherwise people may apply FC values of 93 t/ha for PFs where the typical value is ~5 t/ha: a huge overestimate for a fire type that applies to circa one million ha a year in US. To continue: the temperate forest FC totals and FC by class both seem way too high. E.g. 42 t/ha for duff as an average for temperate forest fires is already almost ten times typical total FC for prescribed fires which account for a large fraction of the burning. At the least, it may be that some attempt is needed to weight the "type averages" for WF and PF in this ecosystem by their relative occurrence. In addition, as a general consideration, the authors could consider weighting individual studies by the number of measurements in the study.
As pointed out by the reviewer, the presented biome-averaged FC values for the temperate forest may be problematic for certain users. Based on the reviewers' comments, we included several changes for –specifically- the temperate forest biome:

* We expanded Section 2 on the measurements, by stating that –in general- obtaining FC measurements for wildfires is more challenging than for prescribed burns:
P7L12-21: "Most of the studies we found in the literature rely on the planar intersect method (PIM), where fuel measurement plots are typically divided in multiple, randomized smaller subplots. The (small-size) biomass in these subplots is oven dried and weighed both pre- and post-fire to estimate the CC and to determine the FC. The consumption of larger-size material (diameter >10cm) is often estimated based on experimental observations of randomly selected trunks and branches that were identified before the fire (Araújo et al., 1999). The PIM is mainly applied in prescribed burns, and obtaining FC measurements for large wildfires is logistically more challenging but can be based on comparing burned with adjacent unburned patches."

* Within the temperate forest biome we now distinguish between wildfires and

prescribed burns:
P12L32-P13L7: “While tropical fires are largely intentionally ignited to pursue land management goals, the temperate forest is also subject to wildfires. Obtaining FC measurements for wildfires is obviously challenging, so most information is derived from prescribed fires which allow researchers to measure pre-fire conditions. However, these fires may not always be a good proxy for wildfires. For example, wildfires in western conifer forest of the US are often crown fires (while prescribed fires usually only burn surface fuels). Due to potential discrepancies with respect to FC, we distinguished between these fire types in Section 3.2.”

* Several prescribed fire FL and FC measurements from the study of Yokelson et al. (2013) were included, as presented in Table 1c.

* We calculated the biome-averaged values for the temperate forest biome in a different way: instead of focusing on ‘total FC’ studies, we now use all measurements presented in Table 1c. Thus, studies that provide information on one specific fuel class only (e.g. ground fuels (Goodrick et al., 2010)) were also included. Due to this, the calculated biome-averaged FC for the temperate forest biome decreased from 93±79 t ha^{-1} to 58±72 t ha^{-1}, and is now closer to what we expect.

* We expanded the discussion on differences between wildfires and prescribed fires in Section 3.2, and provide the reader with FC values that may be more representative for both fire types:
P25L15-28: “In the temperate forest biome FC was underestimated in GFED3 by 74% compared to the field measurement average for collocated grid cells. In our averaged field measurement estimate we included all measurements presented in Table 1c. As noticed in Section 2.3, it is likely though that studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels) are more representative for wildfires. Prescribed burns, on the other hand, tend to burn less fuel and therefore the studies that only include ground or surface fuels were probably more representative for this fire type. When focusing on studies that provide information on one specific fuel class only, the field average for the temperate forest would be significantly lower (13±12 t ha^{-1}) as well as the discrepancy with GFED3 (+14%). This FC value of 13 t ha^{-1} may be more realistic for prescribed fires, which contribute to roughly 50% of all temperate forest fire emissions in the contiguous United States (CONUS). Still, it remains very uncertain how well FC measured for specific fuel classes is representative for prescribed fires and wildfires.”

* We decided not to label prescribed fires and wildfires in table 1c, since it is not always clear if a study is more representative for one of these fire types. Moreover, the study in Mexico (Yokelson et al., 2007) was actually the only ‘real’ wildfire that was measured.

* The high estimate for duff FC (42 t ha^{-1}) can be explained by the fact that we included measurements from the study of Hille and Stevens (2005 - Mixed conifer forest duff consumption during prescribed fires: tree crown impacts, Forest Science). We now included a few other measurements from Carter et al. (2003), and the average FC for ‘organic soil’ decreased to 25±31 t ha^{-1}.

* In general, we decided not to give more weight to studies reporting more measurement in a certain region to prevent biases.

P8127, L6: The Mexico study should be included in average and weighted by the *relative number of measurements. FL and CC are usually secondary products from measuring FC anyway and the FL definition has not yet been clarified.*

We now included the Mexico study of Yokelson et al. (2007), which slightly lowered the biome-averaged FC for temperate forest.

P8127, L25: very little woody debris on sites subject to frequent PF.

Differences between prescribed fire and wildfire FC are now discussed in more detail in Section 3.2. To provide the reader with more background information on the combustion of sound and rotten woody debris, we now refer to the review paper of Hyde et al. (2011).

P8128, L4: Much of the Asian boreal forest is disturbed by illegal/legal logging in Siberia. Vandergert, P., and Newell, J.: Illegal logging in the Russian Far East and Siberia, Int. Forest. Rev., 5, 303–6, 2003.

We included the following sentence:

P14L14-16: "However, much of the Asian boreal forests are disturbed by (il)legal logging activities (Vandergert and Newel, 2003) which can increase fire activity in more remote regions (Mollicone et al., 2006)."

P8128, L10: Most of the FC in a crown fire can be duff.

The reviewer makes a good point, which clearly stresses the uncertainty of the different fuel type FC values that we presented in Table 2c. We added some discussion on this in the last paragraph of Section 2.4, and refer to the interesting paper of Hille and Stephens (2005):

P15L32-P16L1: "Moreover, it was not always clear is which class certain fuels are consumed: e.g. organic material can be consumed on the ground but also in a crown fire (Hille and Stephens, 2005)."

P8129, L5-8: just properly describe this method near the beginning of the paper, give it acronym and use acronym. The biomass in plots is oven dried and weighed both pre and post fire or at burned and adjacent unburned sites and FC is the difference.

As suggested by the reviewer, we now properly described the method in Section 2 of the paper and used the acronym throughout the remainder of our manuscript:

P7L12-21: "Most of the studies we found in the literature rely on the planar intersect method (PIM), where fuel measurement plots are typically divided in multiple, randomized smaller subplots. The (small-size) biomass in these subplots is oven dried and weighed both pre- and post-fire to estimate the CC and to determine the FC. The consumption of larger-size material (diameter >10cm) is often estimated based on experimental observations of randomly selected trunks and branches that were identified before the fire (Araújo et al., 1999). The PIM is mainly applied in prescribed burns, and obtaining FC measurements for large wildfires is logistically more challenging but can be based on comparing burned with adjacent unburned patches."

P8129, L12: The boreal forest FL average is lower than the temperate forest FL average, but is this only if the co-located boreal peat deposits are ignored? Currently the paper discusses boreal peat separately in Sect 2.9 and it would be useful to provide a little guidance on whether peatlands are a greater percentage of the boreal forest biome than the temperate forest biome and a few words of general guidance on *how to couple the FC data for biomes that overlap geographically.*

Based on the reviewer's comment, we added the following text:

P15L13-21: "Average FL for this biome is for upland forest types. However, deep peatland deposits (see section 2.10) cover about 107 M ha (Zoltai et al. 1998) or 18% of the North American boreal forest zone (Brandt, 2009) and 16% of the northern circumpolar permafrost soil area (Tarnocai et al., 2009). By contrast, peatlands only cover about 0.07 M ha in the temperate zone, which has higher FL overall. Despite low decomposition rates due to a cold, moist climate, the lower FL in the boreal forest region is primarily a result of slower tree growth rates (biomass accumulation) and frequent to infrequent fire disturbance that can remove substantial amounts of fuel."

P8130, L3-6: The direction a mountain slope faces is called "aspect" and aspect has long been known to correlate with ecosystem variability in the temperate zone as well. There should be plenty of references to that if a discussion of this is appropriate. The effect is only insignificant in the tropics where the sun angles are higher. Of course there are wet-side dry-side issues and altitude based variation in mountains worldwide, but not sure a discussion of "sub-grid" variability is appropriate.

We revised the sentence to:

P16L6-9: "Finally, slope aspect has been shown to have an effect as well, with the south facing slopes having the highest FL and FC due to warmer and drier conditions that better favour plant growth and fire intensity than shadowed north faces (Viereck et al. 1986; Turetsky et al., 2011)."

P8130, L10: "forest" to "deforestation" – it's helpful to distinguish between "deforestation" and "accidental" forest fires.

We changed "forest" to "deforestation" and distinguish between deforestation and accidental forest fires now, as explained in previous comments.

P8130, L19-21 and L25-27: Re "Note that two studies represent shifting cultivation measurements and were not included in the biome average calculation." Why are they in the "pasture" table/section then? Aren't they part of some biome and should they be included in some category such as tropical forest?

We agree that shifting cultivation does not completely fit the pasture category, and therefore we included a new 'shifting cultivation' category in Section 2.6.

P8131, L5-7: The ignition pattern seems like an un-needed detail, especially since it is not given for other fires. More importantly probably, the fuel geometry varies globally from short-lived burning of loose residue in the field to long-lasting smoldering combustion of small hand-piles of residue, both hard to detect from space.

We agree that the description of the ignition pattern can be removed, especially since it is not given for other fires.

In addition, we stress the importance of fuel geometry by adding the following text:

P17L27-30: "Moreover, the fuel geometry varies globally from short-lived burning of loose residue in the field to long-lasting smoldering combustion of small hand-piles of residue, and both are hard to detect from space."

P8131, L15: Excellent place to cite the classic work of Yevich and Logan!

We decided to cite the work of Yevich and Logan, which is a classic paper indeed.

P8131, L17: Another good paper on fuel consumption in rice straw burning is Oanh et al., Characterization of particulate matter emission from open burning of rice straw, Atmos. Environ., 45, 493-502, 2011.

Although a clear estimate of fuel consumption is not provided by Oanh et al. (2011), we now included their fuel load measurements of rice straw in our database (available online).

P8131, L18-19: probably doesn't add much to give years of measurements in the text throughout.

We agree, and therefore "Measurements conducted in the crop residue biome were taken between the 1980's and 2010 (Table 1f)" was deleted here.

P8131, L20-22: 88% should be expressed as a fraction to be consistent. Also, isn't 0.88 CC too high for pre-harvest burning, which I understand is the most common type of burning at least globally? It would imply that a) the sugar cane field is almost 90% weeds since pre-harvest burning is to remove undesired plants prior to harvesting the cane, or b) the 0.88 is only for post-harvest burning. Re-examining the study of Lara et al, without providing methodology or references, they simply state that FC for Brazilian sugar cane fields was "about" 20 t/ha. It may be that more reliable info is now available.

We decided to stick to percentages throughout the paper.

The CC for pre- and post-harvest sugarcane in McCarty (2011) is 65%. The 88% CC for all crops (including pre-harvest sugarcane) is taken from the U.S. EPA Greenhouse Gas Inventory Methodology (EPA GHG 2008). We have fixed this citation.

P8131, L22-23 and P8132 L2: 0.88 is expressed as a fraction, but attributed to EPA source on P8132 L2. Whereas earlier the same CC is attributed to both McCarty et al and French et al. It actually doesn't agree that "good" with 0.65 value given on P17, L27. In general it's better to avoid words like "good" and just give percent differences so the reader builds up a quantitative knowledge of well things agree. Also clarify sources if possible.

We appreciate that the reviewer has pointed out this inefficient wording. This line has now been changed to:

P18L4-12: "FC values for different US crop types (McCarty et al., 2011) were used to derive crop-specific FL data (French et al., 2013) and CC values were taken from expert knowledge from agriculture extension agents in Arkansas, Louisiana, Florida, Kansas, and Washington during field campaigns in 2004, 2005, and 2006, as well as from the scientific literature (Dennis et al., 2002; Johnston and Golob, 2004). CC variables ranged from 65% for cotton and sugarcane and 85% for wheat and bluegrass, which are lower but within the range of the CC value (-23 to -3% less than CC of 88%) used by the Environmental Protection Agency (EPA) of 88% (EPA 2008 GHG)."

P8132, L3: eliminate "wildly." This variability is exactly what you expect for growing different monocultures.

"wildly" was deleted.

P8132, L5-8: Is this a good guess or a documented fact with references? And not sure *the FC from the study of Lara et al bears inclusion.*

The reviewer makes a good point, and we have revised this text:
P18L13-18: "FC values varied between different crop types, as shown in Figure 6. For US crops the highest FC was found for seedgrass (10 t ha^{-1}) and rice (8.8 t ha^{-1}), while values for soybeans (0.5 t ha^{-1}) and corn (1.0 t ha^{-1}) were lower. In general, US crop values are assumed in the analysis to be approximately representative of other developed agricultural areas like Brazil and Russia (McCarty et al., 2012), but uncertainty increases for less industrialized agricultural areas in Africa and Asia."

P8132, L24: The FC for chaparral of 31.5 t/ha based indirectly on two studies is higher than the total FL in 3 of 4 studies listed in Akagi et al., 2011 Table 2 and higher than the one study by Hardy et al that actually reports FC in the authors work. Having been to several chaparral fires where only the foliage burned and the charred woody biomass remained. I think this number may be too high, but suggest the authors attempt to consult with experts at CalFire or USFS. Alternately, the Cofer et al FC value may just be unreferenced, recycled "conventional wisdom" whereas the Hardy et al measurement is definitely from a detailed, dedicated FC study. If this is the case, the Hardy et al value may deserve much higher weighting.

The study of Hardy et al. (1996) already deserves a higher weighting since it consists of 3 unique measurement locations, while the study of Cofer III et al. (1988) only provides information for one specific location. Therefore, we decided to not weigh the study of Hardy et al. (1996) even more.
However, for the chaparral biome we added a study of Yokelson et al. (2013), and including their measurements lowered the average FC from 32 t ha^{-1} to 27 t ha^{-1}.

P8132, L23-24: Stick to fractions or percentages for CC. Also, the authors seem to be saying they took the Cofer et al FC and multiplied by (1/.78) to get derived Cofer et al FL and then averaged with Hardy et al FL to get ecosystem average FL. If so, be more explicit.

We decided to stick to percentages throughout the paper.

To be more explicit, we rewrote the sentence to:
P19L2-6: "Since Cofer III et al. (1988) only provided a FC for chaparral burning, we used a CC of 76% (average CC from studies of Hardy et al. (1996) and Yokelson et al., 2013) to derive a FL estimate for the Cofer et al. (1988) study. We then used the FL values of all 3 studies to estimate the biome average FL of 40±23 t ha^{-1}."

P8132, L24-26: The last sentence on this page doesn't make any sense to me. Why would a young and old stand essentially reflect no growth and what is "of and the same counts of FC rates"

To prevent the reader from any further confusion we decided to remove this last sentence.

P8133: L3-4: "Southeast Asia"

"South East Asia" was changed to "Southeast Asia" here and also throughout the remainder of the paper.

P8133, L5: "but only the peat above the water table can burn."

We changed "surface layer can burn as long as it is not waterlogged" to "peat layer above the water table can burn."

P8133, L7: nice pun

Indeed

P8133, L 10-11: What is meant by "(although more variable)"? Also, two more references with tropical peat carbon content, Christian et al., 2003 (JGR) and Stockwell et al 2014 (ACPD) bring total range of peat %C to 53.83 to 59.71.

Since we already provided a range it is obvious that the C content of (tropical) peat varies, and therefore "although more variable" was removed.

We consulted the study of Stockwell et al. (2014) and now refer to their C content range (54 – 60%) for tropical peat.

P8133, L15: It is widely reported that the reason to drain the peatlands was a failed attempt at conversion to rice production and commercial logging doesn't require draining swamps per se. However, some commercial logging also occurred after the fact. You might say "Commercial logging in drained peat swamps has increased their susceptibility to fire."

We changed the text to:

P19L22-23: "Commercial logging in drained peat swamps has increased their susceptibility to fire, especially during droughts (such as during and ENSO event)."

P8133, L18: "four studies provided FC measurements in tropical peatlands . . . " (skip the years throughout).

As suggested by the reviewer, ", conducted between 1997 and 2006" was deleted.

P8133, L19-22: I don't recall seeing pre-fire measurements in most of these peatland studies. In some anyway, I think the FC was estimated simply from post-fire observations of burn depth with prefire conditions reconstructed from adjacent unburned areas.

We agree, and changed the sentence to:

P19L25-26: "In general, post-fire observations of the average burn depth were combined with pre-fire conditions reconstructed from adjacent unburned patches to determine the FC."

P8133, L23: "fire regime" refers to patterns of fire occurrence and not an ecosystem and is misused here and several other places. Suggest "tropical peatland had highest FC ... including overstory"

We deleted "The tropical peat fire regime" and replaced it with "Tropical peatland (including peat soils and overstory)".

P8133, L25-27: Delete "was found to be representative" since there is only one data point! Evidently 314/0.27 was used to calculate 1056 t/ha as the ecosystem average FL? In general for the peatland biome you should make clear when you are considering the peat only and when you are considering the peat plus the rest of the biomass in the ecosystem and also that some peatland fires consume overstory forest fuels, but much of the overstory has already been removed in some peatlands.

Since there is only one data point we deleted "was found to be representative".

Indeed, as stated in P19L27-32, we used an average FL of 314 t ha^{-1} and CC of 27% to estimate an average FC of 1056 t ha^{-1}.

In Table 1i we report in the 'notes'-column which fuel types are considered. We make clear in Section 2.9 that for calculating the biome-averaged values both peat soils and overstory are considered:
P19L27-28: "Tropical peatland (including peat soils and overstory) had the highest FC of all biomes, with an average of 314±196 t ha^{-1}."

P8134, L13-14: In "susceptibility of peat fires to fire during different moisture conditions" delete "fires"?
"peat fires to fire" was changed to "peatlands to fire".

P8134, L16: how will paleoecological studies improve knowledge of FC?
Since an improvement of knowledge of FC from paleoecological studies is not that obvious, we changed the text to:
P20L16-17: "This makes modeling peat fires very difficult and stresses the importance of more field measurements."

P8134, L18-19: This text doesn't make sense as written: "the peat depth was sampled to determine the peat density" L19: is bulk density the same as density? Define "bulk density."
We changed the text to:
P20L19-21: "On each burn site, multiple plots were established and information on the peat density (which is assumed to increase nonlinearly with depth) was used in combination with the burn depth to determine the FC."

P8134, L21: As written this could imply that the two studies had the same average FC value to three significant figures. I think you mean the "average of the two studies." This is a case where the standard deviation of the mean with one study at 42 and the other at 43 very likely underestimates the real uncertainty in the biome average since site to site variability within the studies is much larger than that. Suggest using average uncertainty in this case.
We agree that this can imply that the two studies had the same average FC value to three significant figures, and we indeed mean the "average of the two studies". As suggested, we will present an 'average' uncertainty in this case since the SD presented is likely to underestimate the real uncertainty in this biome. We replaced the text with:
P20L21-24: "No data on FL and CC were provided, but the average FC of the two studies is 43 [42-43] t ha^{-1}. A standard deviation of 25 t ha^{-1} (Turetsky and Wieder, 2001) can be used as the average uncertainty for the boreal peat biome."

P8134, L22-25: Interesting, one might expect the permafrost to prevent deep burning and the hummocks to be better drained and more susceptible to fire?
Interesting finding indeed.

P8135, L5: delete "storage"
"storage" was deleted.

P8135, L10-11: So is there evidence fires are increasing or not?
The reviewer makes a good point, and to emphasize that there <u>is</u> actually an evidence we added a reference and changed the text to:
P21L6-8: "However, the evidence of increasing fire frequency and larger extent of the

fires in the arctic (Hu et al., 2010) may represent a positive feedback effect of global warming, so in the future more fires may occur in this biome (Higuera et al. 2011)."

P8135, L27: change "good" to "sufficient" or somehow indicate the problem is quantity and not quality.

"good" was changed to "sufficient".

P8136, L8: Shouldn't "fire occurrence" be "fuels"? In general, there is more to this than geographic coverage. More complex systems require a larger number of samples to have confidence in the mean and/or trends. The authors may want to consider whether these final sections really prove geographic trends or add new insights beyond what has already been presented and delete them if not.

Indeed, "fuels" could be "fire occurrence" as well, and we changed in it in the text.

Although we agree that there is more to it than geographic coverage, we want to provide the reader some insight on the usefulness of these biome-averaged values, given the amount of field measurements that are currently available. In the end of the Section we summarize:

P23L11-18: "Coming back to the question posed in the beginning of this section, we think care should be taken with using biome-average values. They provide a guideline but the path forward is to continue developing models or remote sensing options that aim to account for variability within biomes, and use the database accompanying this paper to constrain these models, rather than to simply use biome-average values (further discussed in Section 3.2). Use of FC for specific vegetation types within broader biomes (like the different crop types as presented in Figure 6) or fuel categories offers an interesting alternative, and is further discussed in Section 3.4."

P8136, L18: change "in not now" to "is not now"?

We replaced the sentence with:

P22L12-15: "As mentioned for the 'Tundra', where fire may become increasingly important as the region warms, the one set of field samples included in this review may not be a representative of past and future fire."

P8137, L3-5: in general CC can increase as the dry season is prolonged as argued elsewhere for savanna fires (Akagi et al., 2011).

As discussed in a previous comment, we added the following text:

P22L26-29: "In general, both FC and CC may increase over the course of the dry season as large diameter fuels dry out. This was also suggested by Akagi et al. (2011) for the savanna biome, and consistent with a seasonal decrease in MCE as proposed by Eck et al. (2013)."

P8137, L13-14: The forestry literature has dozens of tropical forest biomass measurements for forests of specific ages. They tend to show a nice increasing trend. Here the authors note that "primary tropical evergreen forest, tropical evergreen second-growth forest, and tropical dry forest" have different FC values. I suggest that these categories (or numerical stand age if available) be indicated in the table for models with access to that sort of detailed vegetation information.

We indicated this partly in the 'note' column of the different tables, but since some studies include more than one forest 'age' it was rather difficult to fit. Therefore, we refer the reader/modeler/user to the excel-database that is available online at www.globalfiredata.org/FC, where more detailed information can be found.

P8137, L16-19: Re "Clearly, the definition of a certain biome is not always straightforward, and the regional discrepancies found within the different biomes should be taken into account when averaged values are interpreted and used by the modeling communities" So here the authors seem to claim that geographic differences in the measurements within the same nominal "biome" are statistically significant, but I don't think that has been proven?
We agree that this may confuse the reader, and therefore we rewrote the sentence so it is not obvious that these geographical differences are statistically significant:
P23L7-10: "Clearly, the definition of a certain biome is not always straightforward, and uncertainty regarding regional discrepancies within the different biomes should be taken into account when averaged values are interpreted and used by the modeling communities."

P8137, L22: delete "more" since todays models need values to use now.
The sentence was changed to:
P23L12-16: "They provide a guideline but the path forward is to continue developing models or remote sensing options that aim to account for variability within biomes, and use the database accompanying this paper to constrain these models, rather than to simply use biome-average values (further discussed in Section 3.2)."

P8137, L20-26: These could be good ideas if they work, but then give some citations to some of these models and at least a summary of how well validated they are. Or a hint that such a discussion is in next section?
We added "further discussed in Section 3.2".

P8138, L10: define "grid cell"
We replaced "grid cell" with "modeling grid cell". To prevent confusion, we deleted "pixel" and replaced it with "grid cell" throughout the text.

P8138, L12: define "pixel"
To be consistent, we deleted "pixel" and replaced it with "grid cell".

P8138, L13: define "fractionation" and explain how this calculation was done in clear terms
We included a more clear explanation on how GFED3 FC values are calculated:
P23L28-P24L2: "To calculate FC we divided the GFED3 total biome-specific emissions estimates (g Dry Matter) in every modeling grid cell by the total burned area observed for every grid cell. Since one grid cell may consist of multiple biomes we followed the GFED3 fractionation of emissions estimates, which represents the contribution of a certain biome to total emissions within one grid cell. Biome-specific information on the area burned within one grid cell was not available, and therefore we assumed that burned area followed the same fractionation as the GFED3 emissions estimates."

P8138, L13-14: define "regions" and "time period" explain why and how seriously does this over/under estimate biome average and is it expected to be biased?
In general, it's a better test of the model to compare GFED values spatially and

temporally as closely as possible to the published measurements, because the ability to accurately portray trends or geographic variability (or lack there-of) is the main justification for the extra complexity of using the model. It's not clear at the beginning of the discussion that this apparently is the objective as revealed finally at L17.

To provide the reader with a more clear explanation, we added the following text: P24L2-8: "This assumption may over- or underestimate biome-averaged GFED3 FC values: For example, in a deforestation grid cell that consists of savannas and tropical evergreen forests, the contribution of savanna fire emissions to total emissions can be small, even when the contribution of savanna burned area to total burned area observed in a grid cell is actually quite large. In this specific case - when assuming that burned area followed the same fractionation as the emissions- the estimated FC of savannas would be overestimated."

Indeed, it is a better test of the model to compare GFED3 values spatially and temporally as closely as possible to the published measurements. Therefore we decided to only present a comparison of field measurements with co-located GFED3 grid cells, and the comparison with biome-averaged FC values of GFED3 was removed. Although the latter type of comparison may give some useful insight on how well the different biomes are represented by the GFED3 modeling framework, we think that it is outside the scope of our paper to discuss these findings.

P8138, L21: add "co-located" before "GFED3"

"co-located" was added before "GFED3".

P8138, L27-28: To be objective, another possibility that should be mentioned is that GFED underestimates the fire return interval.

We agree, and we now provide more detail on possible causes for the discrepancies: P24L21-29: "A possible cause for these discrepancies is that field campaigns tend to focus on frequently burning areas, so fuels do not have the time to build up and increase their FL (van der Werf et al., 2010). Because of the relatively coarse 0.5° resolution of GFED3, the fire frequency in GFED is the average of more and less frequently burning patches, and thus potentially longer than in field sampling sites. On the other hand, only a very small portion of the land's surface burns annually (van der Werf et al., 2013). Improved resolution for the models may help to alleviate this problem and bring model values closer to the field measurements, although it is very unlikely this is the only reason for the noted discrepancy."

P8139, L3 "difficulty" to "uncertainty"

This whole sentence was removed, for reasons explained above.

P8139, L4-6: Improving models will not make the field measurements more representative. As far as improving the models, a simple statement that it will happen seems like unsupported, vague speculation. If some specific model advance is planned this could a good place to describe it in concrete terms. Otherwise change "will" to "may"

We changed "will" to "may"

Moreover, we modified the text: P24L27-29: "Improved resolution for the models may help to alleviate this problem and bring model values closer to the field measurements, although it is very unlikely this is the only reason for the noted discrepancy."

P8139, L10: The statement about "repeated fires" doesn't make any sense yet. Do you mean you increased the fuel consumption for some burned areas to account for follow- on attempts within the same dry season to burn residual material that failed to burn in the first fire of that dry season? All ecosystems have repeated fires at some time scale – especially the savanna so this needs to be clarified. In general, the paper needs to be written so that people who did not do these calculations know exactly what you did.

We acknowledge that the statement needs to be clarified, and therefore we changed the text to:

P24L32-P25L5: "This discrepancy may be partly explained by the fact that repeated fires in the tropical forest domain (when forest slash that did not burn in a first fire is subject to additional fires during the same dry season) are not always included in the field measurements. Within GFED3, on the other hand, these repeated fires were modeled by the number of active fires observed in the same grid cell (fire persistence), which yields information on the fuel load and type of burning (Morton et al., 2008; van der Werf et al., 2010)."

P8139, L18: Another reason to think about providing a column with rough or actual forest age and maybe even fitting a FC vs forest age relationship.

As discussed previously, we indicated this partly in the 'note' column of the different tables, but since some studies include more than one forest 'age' it was rather difficult to fit. Therefore, we refer the reader/modeler/user to the excel-database that is available online at www.globalfiredata.org/FC, where more detailed information can be found.

P8139, L19-28: Wildfire fuel consumption is higher than prescribed fire fuel consumption according to conventional wisdom, common sense, and the data in Table 1 (I think, it would help to label each fire as PF or WF).

We refer the reviewer to his third general comment, where we explain which modifications were made throughout the paper to better distinguish between wildfire and prescribed fire FC.

P8139, L21: "focused" or "included only" or "9 out 10" please be specific.

"focused on" was changed to "included".

P8139, L23: what do you mean by "ground fuels" litter plus duff, duff plus roots, dead and downed wood included? Define terms near beginning of paper and then use as consistently as possible.

Differences in US and Canadian definitions in fuel categories are minor; sometimes, definitions are not exactly the same between scientists in the same country. As long as the definitions are clearly explained (as currently done on P7L23-24 and P7L31-P8L4) we believe that all scientists will understand. To clarify, we did include some changes. All references to "duff" were removed from the text as this is a general forester's term, and we replaced it with "organic soil".

P8139, L25: prescribed fires tend to burn less fuels and the studies that do not include canopy fuels were probably for prescribed fires. While it is easy to imagine the CASA model generating grass and litter and then GFED using a CC assumption

to burn some of that grass and litter, I have no clue how FC is calculated in GFED for a complex forest environment and a paragraph summarizing that would be useful. Without that, this section and important comparisons will be enigmatic.
To make this section less enigmatic, we decided to remove the comparison with GFED3 FC for the whole biome. Although this comparison may give some useful insight on how well the different biomes are represented by the GFED3 modeling framework, we think that it is outside the scope of our paper to discuss these findings. We decided to only present a comparison of field measurements with co-located GFED3 grid cells.

Moreover, we now included a more clear explanation on how GFED3 FC values are calculated. A more detailed description can be found in Van der Werf et al., 2010:
P23L25-P24L8: "GFED3 fire emissions estimates (monthly 0.5°×0.5° fields) are based on estimates of burned area (Giglio et al., 2010) and the satellite-driven Carnegie-Ames-Stanford Approach (CASA) biogeochemical model (van der Werf et al., 2010). To calculate FC we divided the GFED3 total biome-specific emissions estimates (g Dry Matter) in every modeling grid cell by the total burned area observed for every grid cell. Since one grid cell may consist of multiple biomes we followed the GFED3 fractionation of emissions estimates, which represents the contribution of a certain biome to total emissions within one grid cell. Biome-specific information on the area burned within one grid cell was not available, and therefore we assumed that burned area followed the same fractionation as the GFED3 emissions estimates. This assumption may over- or underestimate biome-averaged GFED3 FC values: For example, in a deforestation grid cell that consists of savannas and tropical evergreen forests, the contribution of savanna fire emissions to total emissions can be small, even when the contribution of savanna burned area to total burned area observed in a grid cell is actually quite large. In this specific case - when assuming that burned area followed the same fractionation as the emissions- the estimated FC of savannas would be overestimated."

We expanded the discussion on the differences between prescribed fires and wildfires in both temperate and boreal forest biome:
P25L15-P26L4: "In the temperate forest biome FC was underestimated in GFED3 by 74% compared to the field measurement average for collocated grid cells. In our averaged field measurement estimate we included all measurements presented in Table 1c. As noticed in Section 2.3, it is likely though that studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels) are more representative for wildfires. Prescribed burns, on the other hand, tend to burn less fuel and therefore the studies that only include ground or surface fuels were probably more representative for this fire type. When focusing on studies that provide information on one specific fuel class only, the field average for the temperate forest would be significantly lower (13±12 t ha^{-1}) as well as the discrepancy with GFED3 (+14%). This FC value of 13 t ha^{-1} may be more realistic for prescribed fires, which contribute to roughly 50% of all temperate forest fire emissions in the contiguous United States (CONUS). Still, it remains very uncertain how well FC measured for specific fuel classes is representative for prescribed fires and wildfires. This issue also counts for boreal forests, where GFED3 overestimated the field measurements by almost 80%. When only including studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels), the field average for the boreal forest would increase from 35±24 t ha^{-1} to 39±19 t ha^{-1} and the discrepancy with GFED3 would decrease (from +79 to +60%). This value of 39±19 t ha^{-1} may be more representative for boreal wildfires.

Note that for temperate and boreal forest measurements sometimes the more restrictive definition of FL (as presented in Section 1) was used, and this can have an impact on FC values as well; if one applies a CC calculated with respect to a restrictive pre-fire FL to total biomass available, the overall FC that was estimated can be too high."

P8140, L11: 1.6 t/ha (also in Table 3) seems like it has to be a misprint as that number is not physically realistic. If not, how can GFED be more than 50 times lower than the measurement average?
That is a very interesting question, which needs further investigation. We removed the comparison with GFED3 FC for the whole biome, for reasons explained in the previous comment.

P8140, L12, It may not be that all the measurement locations were "wrong," but that the overall sample is skewed. It may also be the mix of fire types that might be non-representative. Or the model could be wrong. Change "indicates that the" to "suggests that the mix of" and add "and fire types" before "shown." It's nice to consider all the data, but a review article may justify having to reject some data.
This part of the text was removed for reasons explained in the previous comments.

P8140, L13: "counts" to "holds"
This part of the text was removed for reasons explained in the previous comments.

P8140, L14: The authors may find that the USDA Cropland by crop type: database is helpful to fine-tune their comparisons http://www.nass.usda.gov/research/Cropland/SARS1a.htm
We used this CDL database in the creation of the French et al. (2013) fuel load map of the contiguous United States (CONUS) to improve the cropland fuel types classification, spatial distribution, and calculation of fuel load in CONUS.

P8140, L17: "measurement" (no "s").
This part of the text was removed for reasons explained in the previous comments.

P8140, L20: change first "on" to "of" and delete "studies on"
This last paragraph was completely removed, since it did not go well together with the rest of Section 3.3.

P8140, L21: Many FL measurements exist also for different aged tropical forests in neotropics.
Interesting, and hopefully we can include these measurements in our database in the near future.

P8140, L22: make it clear if the spreadsheet at the link includes the values in the paper and additional values not in the paper both. Instead of saying "it may change the average" say how it does change the average if included, but also why that was not considered appropriate for the paper.
This last paragraph was completely removed, since it did not go well together with the rest of Section 3.3.

P8141, L1-29: Few things could be improved. First, the FRP/FC relationship is given to three significant figures with no uncertainty three times, which is unrealistic. 0.316 +/- 0.05 seems more reasonable. Plus that's only when there is no obscuration at all. FRP is at best sensitive to the momentary rate of fuel consumption, but not the total FC for the whole fire. FRP could be indirectly related to FC if all of some fire product was detected and that products emission factor was known and highly constrained. But emission factors are variable. And when viewing from space in practice, if a cloud/cloudmask covers the smoke, but not the hotspot, the emission/FRP is essentially zero. When the cloud/cloudmask covers the hotspot, but not the smoke, the emission/FRP is infinite. Thus, the relationship is likely to be fairly uncertain. FRP has to be integrated over the life of the fire to get FRE to estimate FC more directly. Geostationary data (with fifteen minute time resolution) would be better than MODIS for this, but many tropical fires are small and only live 15-30 minutes. In general observed, emitted energy is going to be less than actual energy, but there may be an over-/undercorrection to produce final estimate. The second paragraph says that FC measurements by FRP are "anecdotal" but the third paragraph gives a FC from FRP with no uncertainty attached and seems to indicate that the approach works almost perfectly. Maybe what is missing is whether the "FRP-based" calculation of FC was tuned to match available measurements or if there was fortuitous cancellation of errors, etc. Also be clear if it "worked" at an ideal point or on a broad landscape scale.

Based on the reviewer's comments we modified Section 3.3: we now included uncertainty estimates, and provided more detail on the (uncertainty of the) FRE-FC relationship for different fire types:

P26L17-P28L7: "Besides a comparison with GFED3 data, we performed a comparison of field measurement averages with fire radiative energy (FRE, time-integrated FRP) derived estimates as well. The basis of the FRE approach for estimating FC is that the heat content of vegetation is more or less constant, and that the FRE released and observed through a sensor can be converted to FC by the use of a constant factor, which was found to be 0.368±0.015 kg MJ^{-1} across of a range of fuels burned under laboratory conditions (Wooster et al., 2005). More recent field experiments, however, indicated that the conversion factor might be slightly lower for grasslands in North America (Kumar et al., 2011; Schroeder et al., 2014). Smith et al. (2013) investigated the relationship between FC and FRE for pine needles with different fuel moisture contents, and found that FRE released per kilogram biomass consumed decreased with fuel moisture content due to the energy required to evaporate and desorb the water contained in the fuel. Thus, corrections for FRE based FC assessments may be needed for fuels that burn at higher fuel moisture contents. Differences in heat content of fuel may introduce additional variation: For example, a clear relationship between FRE and FC has not yet been demonstrated for fires that burn mostly in the smoldering stage, like organic soils in boreal forests or large woody debris and trunks in tropical deforestation regions. Another potential source of uncertainty in the relation between satellite-derived FRE and FC is the correction for atmospheric disturbances, which may significantly alter FRP retrievals and hence estimates of FC (Schroeder et al., 2014). Note that, currently, atmospheric correction is not performed for the standard fire products derived from MODIS. Moreover, Schroeder et al. (2014) also indicate that cloud masking in the MODIS FRP product may lead to FRP underestimates as hotspots under thick smoke may be erroneously masked out.

Despite all these uncertainties this approach is promising and there is a number of studies that relate FRE to FC on regional (Roberts et al., 2011; Freeborn et al., 2011) to global scales (Vermote et al., 2009; Ellicott et al., 2009), and Kaiser et al. (2012) used FRE to represent biomass burning in an operational chemical weather forecast framework. However, since such estimates can be derived independently of burned area, only a limited number of studies allow a straightforward comparison to the FC values given in mass units per area burned from the field experiments used in this study.

A common finding of FRE-based estimates is that FC is generally lower than GFED estimates, as shown by Roberts et al. (2011) who estimated FC for Africa through an integration of MODIS burned area and Meteosat Spinning Enhanced Visible and Infrared Imager (SEVIRI) derived FRP and found values that were about 35% lower than GFED. For the savanna biome a median FC of ~4 t ha^{-1} was found for grassland and shrubland. This corresponds relatively well with the mean of 4.3±2.2 t ha^{-1} and 5.1±2.2 t ha^{-1} found in grassland savanna and wooded savanna field studies we compiled, respectively. Boschetti and Roy (2009) explored temporal integration and spatial extrapolation strategies for fusing MODIS FRP and MODIS burned area data over a single large fire in a grassland dominated area with sparse eucalypt trees in northern Australia. They estimated a FC range of 3.97-4.13 t ha^{-1}, which is well within the range found in the Australian FC studies summarized in Table 1. Kumar et al. (2011) exploited properties of the power law distribution to estimate FC from FRP for an Australian savanna and a study area in the Brazilian Amazon. While their FC estimate of 4.6 t ha^{-1} of the Australian site is similar to the temporal integration results of Boschetti and Roy (2009), the estimate for the Brazilian site is above 250 t ha^{-1} and thus substantially higher than the biome-averaged value for Brazilian tropical forest (117±56 t ha^{-1}).

In general, realistic values are often obtained for well-observed fires, but unrealistically low or high values can often occur especially for smaller fires due to the sparseness of FRP observations and inaccuracies in the temporal interpolation and the burned area estimates. While FRE seems to provide realistic estimates under a range of conditions, issues of undersampling of FRE and -maybe less important - the conversion of FRE to FC still remain to be addressed more completely in order to derive spatially explicit FC estimates using the FRP approach."

P8142, L5-6: Most of the burning in Brazilian Amazon is pasture fires or crop residue fires so 250 t/ha is really high unless the study site was small enough to only include slashed and burned tropical forest.

The FC estimate of 250 t ha^{-1} from Boschetti and Roy (2009) is indeed very high for a region where a substantial part of the burning is coming from pasture fires, crop residue burning and shifting cultivation. However, GFED FC for the co-located grid cells estimated a FC of 215 t ha^{-1}, which is relatively close to the Boschetti and Roy (2009) estimate. Since a clear relationship between FRE and FC has not yet been demonstrated for fires with a significant consumption of smoldering prone fuels, like e.g. trunks in tropical deforestation regions, we now point out that the FRE derived FC for tropical forest regions is highly uncertain:

P26L30-P27L1: "Differences in heat content of fuel may introduce additional variation: For example, a clear relationship between FRE and FC has not yet been demonstrated for fires that burn mostly in the smoldering stage, like organic soils in boreal forests or large woody debris and trunks in tropical deforestation regions."

P27L29-33: “While their FC estimate of 4.6 t ha^{-1} of the Australian site is similar to the temporal integration results of Boschetti and Roy (2009), the estimate for the Brazilian site is above 250 t ha^{-1} and thus substantially higher than the biome-averaged value for Brazilian tropical forest (117±56 t ha^{-1}).”

P8144, L1: “reasonable” to “reasonably” and add “co-located” before “measured” Somewhere in conclusions the fact that measured/GFED3 FC for temperate forest is 93/1.6 unless this is rectified during the revisions.

As suggested by the reviewer, we changed “reasonable” to “reasonably” and added “co-located” before “measured”

The comparison with GFED3 FC for the whole biome was removed, and therefore the temperate forest discrepancy was not mentioned in the Summary Section.

Table 2b: “logs” versus “large woody debris” same thing or different?

To prevent confusion, and given the fact that both fuel types are sometimes overlapping, we now merged them into the new category ‘Woody debris (>20.5cm), Trunks’

Table 2c: the FL of the litter alone is greater than the total FL in Table 5 of Yokelson et al 2013. As a former wildland firefighter, prescribed fire lighter, etc I think 60% CC for duff and 96% CC for dead downed logs is only applicable to extreme fire conditions. These fuels quite often experience only surface charring. I would say more typical is 10% CC for each of these fuel components during wildfire season.

Measurements from the study of Yokelson et al. (2013) were now included in our database, and their total FL was indeed lower than the FL for litter as presented in Table 2c. Our estimates are based on all peer-reviewed studies that provided specific information on FL, CC, and FC for different fuel classes. FL of litter was found to be high, and the same holds for the CC of dead woody debris. However, these findings are based on a few studies only, and therefore we emphasize in Section 3.4 that “more field measurements are needed to decrease the uncertainty and better understand the variations found“.

Fig. 2: Use “Wooded Savanna” instead of “Woodland” which is easier to confuse with forest?

We replaced ‘woodland’ with ‘wooded savanna’ in Figure 2. Moreover, “grassland” was changed to “grassland savanna”.

Fig 6: make clear all US (McCarty) except Lara is Sugarcane Brazil.

The figure caption was changed to: “Fuel consumption (FC) rates for different US crop types as reported by McCarty et al. (2011), and Brazilian sugarcane (Lara et al., 2005).”

Response to referee #2 (Anonymous)

<u>General Comments:</u>

The paper "Biomass burning fuel consumption rates: a field measurement database" addresses an important topic in biogeochemical modeling and atmospheric sciences and is a substantial contribution to scientific progress within the scope of Biogeosciences. The database assembled and presented in this study will be of great value to researchers in many fields. The paper well organized and it is well written. I recommend this paper for publication in Biogeosciences following some minor revisions/edits.

<u>Specific Comments:</u>

Temperate fires/boreal fires. Fires in the tropics and savannas are largely intentionally ignited to pursue some land management goal. However, boreal and temperate burning is large wildfires. Obtaining fuel consumption measurements for wildfires is obviously challenging. Therefore studies often involve intention ally ignited fires / prescribed fires which allow researchers to set up plots prior to the planned ignition. However, these fires may not be a proxy for wildfires. For example, wildfires in western conifer forest of the US frequently involve significant canopy fire (while prescribed fires usually do not). No canopy fuel consumption noted in Table 2c. Also, are there similar prescribed vs. wildfire differences for Eucalypt forest in Australia? Please comment and discuss the possible bias of relying on planned/prescribed fire studies to represent fuel consumption for wildfires in temperate and boreal forest.

In general, fuel consumption of wildfires is higher than prescribed fire fuel consumption according to conventional wisdom, and also according to the data presented in Table 1c of our paper. To emphasize these differences within both temperate and boreal forest biome, we made the following changes:

* We expanded Section 2 on the measurements, by stating that –in general- obtaining FC measurements for wildfires is more challenging than for prescribed burns:
P7L12-21: "Most of the studies we found in the literature rely on the planar intersect method (PIM), where fuel measurement plots are typically divided in multiple, randomized smaller subplots. The (small-size) biomass in these subplots is oven dried and weighed both pre- and post-fire to estimate the CC and to determine the FC. The consumption of larger-size material (diameter >10cm) is often estimated based on experimental observations of randomly selected trunks and branches that were identified before the fire (Araújo et al., 1999). The PIM is mainly applied in prescribed burns, and obtaining FC measurements for large wildfires is logistically more challenging but can be based on comparing burned with adjacent unburned patches."

* Within the temperate forest biome we now distinguish between wildfires and prescribed burns:
P12L32-P13L7: "While tropical fires are largely intentionally ignited to pursue land management goals, the temperate forest is also subject to wildfires. Obtaining FC measurements for wildfires is obviously challenging, so most information is derived from prescribed fires which allow researchers to measure pre-fire conditions. However, these fires may not always be a good proxy for wildfires. For example, wildfires in western conifer forest of the US are often crown fires (while prescribed

fires usually only burn surface fuels). Due to potential discrepancies with respect to FC, we distinguished between these fire types in Section 3.2.”

* Several prescribed fire FL and FC measurements from the study of Yokelson et al. (2013) were included, as presented in Table 1c.

* We calculated the biome-averaged values for the temperate forest and boreal forest biome in a different way: instead of focusing on ‘total FC’ studies, we now use all measurements presented in Table 1c. Thus, studies that provide information on one specific fuel class only (e.g. ground fuels) were also included. Due to this, the calculated biome-averaged FC for the temperate forest biome decreased from 93±79 t ha^{-1} to 58±72 t ha^{-1}, and the biome-averaged FC for boreal forest decreased from 39±19 t ha^{-1} to 35±24 t ha^{-1}. For both biomes, the difference between the field measurements and GFED3 FC decreased.

* We expanded the discussion on differences between wildfires and prescribed fires in Section 3.2, and provide the reader with FC values that may be more representative for both fire types:

P25L15-P26L4: “In the temperate forest biome FC was underestimated in GFED3 by 74% compared to the field measurement average for collocated grid cells. In our averaged field measurement estimate we included all measurements presented in Table 1c. As noticed in Section 2.3, it is likely though that studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels) are more representative for wildfires. Prescribed burns, on the other hand, tend to burn less fuel and therefore the studies that only include ground or surface fuels were probably more representative for this fire type. When focusing on studies that provide information on one specific fuel class only, the field average for the temperate forest would be significantly lower (13±12 t ha^{-1}) as well as the discrepancy with GFED3 (+14%). This FC value of 13 t ha^{-1} may be more realistic for prescribed fires, which contribute to roughly 50% of all temperate forest fire emissions in the contiguous United States (CONUS). Still, it remains very uncertain how well FC measured for specific fuel classes is representative for prescribed fires and wildfires. This issue also counts for boreal forests, where GFED3 overestimated the field measurements by almost 80%. When only including studies that provided a total FC (i.e. the FC of ground, surface and/or crown fuels), the field average for the boreal forest would increase from 35±24 t ha^{-1} to 39±19 t ha^{-1} and the discrepancy with GFED3 would decrease (from +79 to +60%). This value of 39±19 t ha^{-1} may be more representative for boreal wildfires. Note that for temperate and boreal forest measurements sometimes the more restrictive definition of FL (as presented in Section 1) was used, and this can have an impact on FC values as well; if one applies a CC calculated with respect to a restrictive pre-fire FL to total biomass available, the overall FC that was estimated can be too high.”

* The study of Hollis et al. (2010) provided FC estimates for a mixture of prescribed fires and wildfires in Australian eucalypt forests. However, no significant difference in FC was found for both fire types.

* No canopy FC was noted in Table 2c, since this fuel class was not clearly distinguished in the refereed literature. Many studies only provided a ‘total’ FC estimate.

Sect. 2.3 P8127, L24 – 27: The authors should consult & cite Hyde et al. (2011) “The *combustion of sound and rotten coarse woody debris: a review", International Journal of Wildland Fire, 20, 163-174.*

We consulted the review paper of Hyde et al. (2011) and now refer to their findings on the difference between sound and coarse woody debris consumption:

P14L1-4: "Although this difference was observed in a few other studies as well, little research is available on comparing the physical and chemical properties of sound and rotten woody debris, which is likely to affect the FC (Hyde et al., 2011)."

Sect. 2.4: Of the fires used for the biome averages were these studies primarily pre-scribed fires or wildfires? Are there differences in FC for the two types in North America? If so, could this bias the results? Please comment.

These comments were addressed in the reviewers' first specific comment.

Sect. 2.6 P8132, L8-10: Is the sugar cane FC difference between US and Brazil due to FL?

Unfortunately, this interesting question remains unanswered since the study of Lara et al. (2005) only presents a FC estimate and did not provide any information on the CC for Brazilian sugarcane. Note that a larger number of measurements are required to conclusively say whether these differences between US and Brazil sugarcane are statistically significant.

P8133, L13-15, sentence starting "Results from several..." I don't completely follow this statement. Do the authors mean that some studies show a link between burning depth and depth of drainage? Please clarify.

We indeed mean that measurements indicate that there is a link between the burning depth and the depth of drainage (which in its turn relates to droughts). To be clearer we restated this sentence:

P19L20-21: "Results from several field measurements indicate a link between this burning depth and the depth of drainage (Ballhorn et al., 2009)."

Sect 3.2 Please note the GFED3 pixel size.

We now included the temporal and spatial resolution of GFED3 emissions estimates in the text:

P23L25-28: "GFED3 fire emissions estimates (monthly 0.5°×0.5° fields) are based on estimates of burned area (Giglio et al., 2010) and the satellite-driven Carnegie-Ames-Stanford Approach (CASA) biogeochemical model (van der Werf et al., 2010)."

P8138, L9-10 States: "Since biome-specific information on the area burned within one pixel was not available,. . ." which implies each GFED3 pixel (0.5 degree x 0.5 degree?) may have multiple biomes. Therefore, it is difficult to interpret the comparison of first number in column 5 of Table 3 with the field study FC, P8138, L14-19: "In the fifth column FC rates per unit burned area of GFED3 are shown for the collocated grid cells, i.e. grid cells in which measurements were taken, (first number)". Could the FC in a GFED3 pixel be dominated by a biome different from that of the field study? Could the differences results from mapping of biome type rather than FL and CC. Could this explain the large difference between the first and second numbers of column 5 for crop residue and tropical forest? Please comment/clarify.

Indeed, a GFED3 grid cell can have multiple biomes. We included a more clear

explanation on how GFED3 FC values are calculated:
P23L28-P24L8: "To calculate FC we divided the GFED3 total biome-specific emissions estimates (g Dry Matter) in every modeling grid cell by the total burned area observed for every grid cell. Since one grid cell may consist of multiple biomes we followed the GFED3 fractionation of emissions estimates, which represents the contribution of a certain biome to total emissions within one grid cell. Biome-specific information on the area burned within one grid cell was not available, and therefore we assumed that burned area followed the same fractionation as the GFED3 emissions estimates. This assumption may over- or underestimate biome-averaged GFED3 FC values: For example, in a deforestation grid cell that consists of savannas and tropical evergreen forests, the contribution of savanna fire emissions to total emissions can be small, even when the contribution of savanna burned area to total burned area observed in a grid cell is actually quite large. In this specific case - when assuming that burned area followed the same fractionation as the emissions- the estimated FC of savannas would be overestimated."

Regarding the large differences between the first and second number of column five: We decided to remove the comparison with GFED3 FC for the whole biome. Although the this comparison may give some useful insight on how well the different biomes are represented by the GFED3 modeling framework, we think that it is outside the scope of our paper to discuss these findings. Instead, we now only present a comparison of field measurements with co-located GFED3 grid cells.

Section 3.2. Care should be taken in identifying "outliers". The mismatch between the mean and median is not surprising given that surface and ground fuels tend to have a log-normal or weibull distributions. At any given site the median value may provide the best guess. However, over large areas landscapes or forest stands with very high fuel loading ("outliers") should be important and excluding such sites or using the median value would lead to an erroneously low value. For example see Keane et al. (2013) Forest Ecology & Management 305, 248-263. This study examined FL data from >10,000 forests plots in the western US and found that even within specific forest types there was considerable variability.
We agree on the reviewer that care should be taken in identifying outliers. A large part of this section was changed, and now a more conclusion on how these biome-averaged values can be used is given:
P26L5-13: "For most biomes, a few field measurements had a FC that was an order of magnitude larger than the other values listed in Table 1, which explains the discrepancy between the median and average FC values that was sometimes found (e.g. the 'Australia and Tasmania' region in Figure 4). By neglecting these 'outliers' the biome-averaged values may change significantly, but this could lead to erroneously low or high estimates as well. In general, FC shows large variability between biomes, within biomes, and even within a specific fuel type. FC is often hard to measure, and since only a few measurements are available for some biomes, care should be taken when using the biome-averaged values presented in this paper."

Sect. 3.3 It may be worth noting that the FRP-based studies largely involved fires (savannas, grasslands, woodlands) in which the fuel consumed was mostly fine fuels – grasses and litter, fuel that burn predominantly by flaming combustion. I do not believe that a relationship between FRP/FRE and fuel consumption has been demonstrated for fires with significant consumption of smoldering prone fuels duff *and coarse woody debris. It is unclear that duff, especially lower layers would have a heat content similar to other components (see e.g. van Wagtendonk et al. (1998) Int. J. Wildland Fire, 8 147-158). Also, it is not clear that the fraction of heat released as radiant energy during the smoldering combustion of duff and coarse wood would be the same as that for flaming combustion of fine fuels upon which FRP-based FC relationships have been based.*

A substantial part of Section 3.3 was modified, and we now provide more information on the FRE-FC relationship. Moreover, we emphasize that this relationship is less clear for smoldering fires:
P26L25-P27L1: "Smith et al. (2013) investigated the relationship between FC and FRE for pine needles with different fuel moisture contents, and found that FRE released per kilogram biomass consumed decreased with fuel moisture content due to the energy required to evaporate and desorb the water contained in the fuel. Thus, corrections for FRE based FC assessments may be needed for fuels that burn at higher fuel moisture contents. Differences in heat content of fuel may introduce additional variation: For example, a clear relationship between FRE and FC has not yet been demonstrated for fires that burn mostly in the smoldering stage, like organic soils in boreal forests or large woody debris and trunks in tropical deforestation regions."

<u>Technical Comments</u>

P8134, L14: change 'peat fires' to 'peat lands'

"peat fires" was changed to "peatlands".

P8136, L18: change 'fire in not' to 'fire is not'

We changed the sentence to:
P22L12-15: "As mentioned for the 'Tundra', where fire may become increasingly important as the region warms, the one set of field samples included in this review may not be a representative of past and future fire."

P8136, L26 – P8137, L3: This sentence is confusing and needs to be rewritten. I do not understand how the fragment "but due to the overall large contribution of forest floor fuels" fits in this sentence

We agree that this sentence is rather confusing, and therefore we replaced it with: P22L21-23: "Although available literature data showed that FC for crown fuels was indeed higher than for surface fuels, more data for especially boreal Russia is needed to confirm this line of thought."

Table 1f. Typo in row 5, CC should = 90% not 0.9?

"0.9 (-)" was changed to "86 (6.0)".