Overview

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 #2 (Anonymous)

General Comments:

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.

Specific Comments:

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 $0.5°\times0.5°$ 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:

P26L5-20: "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 a 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. It is up to the user to assess the implication for their applications: the use of non-average values could be justified if they were produced by a validated model that explains the observed variability in field measurements. Using a non-average value that is within the uncertainty of the biome could also be of interest (or convenient) if it systematically improves representation of e.g. downwind concentrations. Note that in this latter case, the user should consider if a change of other uncertain parameters (e.g. burned area) can or cannot be ruled out."

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:

P26L32-P27L8: "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 (such as peat). 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 with a significant consumption of smoldering prone fuels, like e.g. organic soils in boreal forests or large woody debris and trunks in tropical deforestation regions."

Technical Comments

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)".