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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. These fuel consumption (FC) rates depend 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 rates are either modeled or taken selectively from the literature. We compiled the peer-reviewed literature on FC rates for various biomes and fuel categories to better understand FC rates and variability, and to provide a database that can be used to constrain biogeochemical models with fire modules. We compiled in total 76 studies covering 10 biomes including savanna (15 studies, average FC of 4.6 t DM (dry matter) ha^{-1}), tropical forest ($n = 19$, FC = 126), temperate forest ($n = 11$, FC = 93), boreal forest ($n = 16$, FC = 39), pasture ($n = 6$, FC = 28), crop residue ($n = 4$, FC = 6.5), chaparral ($n = 2$, FC = 32), tropical peatland ($n = 4$, FC = 314), boreal peatland ($n = 2$, FC = 42), 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 were found within the defined biomes: for example FC rates of temperate pine forests in the USA were 38 % higher 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 rates, not only between biomes but also within biomes and fuel classes. This implies that care should be taken with using averaged values, and our comparison with FC rates from GFED3 indicates that also modeling studies 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 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. The burned area can be obtained 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. The FL refers to that portion of the total available biomass that normally burns under specified fire conditions and 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. Both quantities currently 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 (DGVM, e.g. Kloster et al., 2010) or 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, 2005; Kaiser et al., 2012).

FRP relates directly to the rate of fuel consumption (abbreviated as "FC" in the remainder of the paper), which again is proportional to the fire emissions. The FRP method has several advantages compared to the burned area method by Seiler and Crutzen (1980), such as the ability to detect smaller fires and the fact that the fire emissions estimates do not rely on FL or CC. One main 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 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 emissions 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 mean emission factors, but focused on measurement of fresh plumes only and provided more biome-specific information.

To improve and validate fire emissions models, it is crucial to gain a better overview of available FC measurements, where FC is the product of FL and CC. 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 comparing the FRP normalized by 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: FL and CC are usually inversely related, and fine fuels (i.e. with a low FL) burn more complete than coarser fuels (i.e. with a high FL). Forested ecosystems in general show relatively little variability in FL over time for a given location, but CC can vary due to weather conditions. Grassland and savanna ecosystems have little variability in CC (which remains high in general), but FL can vary on monthly time scales depending on season, time since fire, and grazing rates. FL in boreal and tropical forests is in the same order of magnitude, 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 boreal region the soil and duff (a layer of moderately to highly decomposed needles, leaves and other organic material found between the mineral soil and litter layer) represent 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. 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. In follow-up papers we aim to better understand 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. The paper is organized as follows: in Sect. 2 we list all the measurements and divide them into 10 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 Sect. 3, and in addition a comparison between the FC field measurements and (1) the values used in the Carnegie–Ames–Stanford-Approach Global Fire Emissions Database (CASA-GFED, van der Werf et al., 2006, 2010) modeling framework, and (2) several FRP-derived estimates, is given. Finally, our results are summarized in Sect. 4.

2 Measurements

Figure 1 provides an overview of the locations where peer-reviewed FC rates were measured in the field, overlaid on mean annual fire 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 vs. 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, where fuel measurement plots are typically divided in multiple, randomized smaller subplots to weigh the pre-fire biomass. After the burn the remaining biomass is then weighed to estimate the CC, and to determine the FC. 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 (duff, 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: 1 h, 10 h, 100 h, and 1000 h and correspond to round woody fuels in the size range of 0–0.635 cm, 0.635–2.54 cm, 2.54–7.62 cm, and 7.62–20.32 cm, 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 deep duff, 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 were 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 ton dry matter per hectare ($\mathrm{t\,ha^{-1}}$), 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 10 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 rate for both the below and aboveground biomass. The data presented in Table 1 focussed on FC rates. Additional studies on FL measurements exist and were not included here, but listed in a spreadsheet that is available online at http://www.falw.vu/~gwerf/fuel_consumption/. 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 Sects. 2.1–2.10.

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). 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 is the most important factor controlling the extent of area burned (Menaut et al., 1991). 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 yr^{-1}. 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 yr^{-1}. This difference is mostly due to the lack of grasses that restrict nitrification in Australian savannas.

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 dense woodland and thus the savanna biome (Ratnam et al., 2011). For calculating averages, we divided the savanna biome into grassland and woodland regions. The savanna measurements presented in Table 1a were taken between 1990 and 2009, and represent 17 unique measurement locations (Fig. 1) taken from 15 different studies. For all measurements conducted, we found an average FL of 7.6 t ha^{-1} and FC of 4.6 t ha^{-1}. The average of the CC values as presented in the different studies indicated a value of 71 %, 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, substantial regional differences were found (Fig. 2): FL and FC rates for South American savannas, 8.2 and 6 t ha^{-1}, respectively, were higher than the ones measured in the savannas of Australia (5.1 and 3.6 t ha^{-1}). Measurements conducted in Africa, contributing to roughly 40 % of all measurements in the biome, showed the lowest FC (3.4 t ha^{-1}) of all regions. Due to the relatively small number of measurements, these findings are not conclusive. To distinguish between grassland and woodland, data of both types of savanna are also provided in Fig. 2. For grassland the average FL was relatively low (5.3 t ha^{-1}) and the CC high (81 %), yielding an average FC of 4.3 t ha^{-1}. Woodlands, on the other hand, had a higher FL (11 t ha^{-1}) but lower CC (58 %), and therefore the average FC of 5.1 t ha^{-1} was only slightly higher as the one found for grasslands. Although data of the Indian woodland study (Prasad et al., 2001) were not shown in Fig. 2, we included them to calculate the averaged values.

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 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 % found for woody fuels with a diameter larger than 2.54 cm (100 h fuel). FC rates for the different fuel types were 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 rates in the savanna biome, for example, the sum of different fuel categories is 5.3 t ha^{-1} and slightly higher than the biome average of 4.6 t ha^{-1}.

2.2 Tropical forest

Tropical rainforests are generally not susceptible to fire except during extreme drought periods 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. However, human activities (selective logging and clear-cut) have resulted in more fire activity in tropical forests. Selective logging can decrease the canopy cover and logging waste and dense undergrowth provide fuels on which fires can spread (Nepstad et al., 1999; Siegert et al., 2001). Fire intensity can be much higher in logged woods, as the photon flux increases due to the decreased canopy cover resulting in fast fuel desiccation and even crown fires may occur (Uhl and Buschbacher, 1985). 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 tons 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 the biomass is slashed in one year and burned in the next year 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, South East 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 planar intersect models. 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 t ha^{-1}, CC averaged 49 %, and the rate of total FC was 126 t ha^{-1}. Since more than 90 % of all measurements were conducted in Brazil (Fig. 3), the biome-averaged values are biased towards measurements conducted in this country. Studies conducted in Mexican and Indonesian evergreen tropical forest reported an average FL of 403 and 237 t ha^{-1}, respectively. Surprisingly, the CC of evergreen tropical forest in Mexico (Hughes et al., 2000b) was the highest of all studies (95 %), resulting in an average FC of 380 t ha^{-1}, which was significantly higher than values found for both Brazil (117 t ha^{-1}) and Indonesia (120 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 differences found, and therefore we also provided data for measurements conducted in primary tropical evergreen forest, second-growth evergreen tropical forest, and tropical dry forest (Fig. 3). FL and FC were largest for primary forests, with average values of 339 t ha^{-1} and 143 t ha^{-1}, respectively. For second-growth forests these values were substantially lower (101 t ha^{-1} and 57 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 rate 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). Logs (diameter > 30 cm) and trunks – although not always taken into account in certain studies – correspond to a large part of the aboveground biomass (FL = 198 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 17 % and FC rate of only 31 t ha^{-1}. Similar to the savanna biome, we found a high CC of at least 73 % for surface fuels with a large area to volume ratio (litter, leaves, and dicots). The small woody fuels (1 h and 10 h) 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 t ha^{-1}), logs (> 30 cm) and trunks (31 t ha^{-1}) and woody debris size classes with a diameter larger than 0.64 cm (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. The 21 unique FC measurement locations for the temperate forest are from sites in North America (12), Australia (7), Tasmania (1) and Mexico (1), and were taken between 1983 and 2009 (Fig. 1, Table 1c). 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 planar transect method. 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 161 t ha^{-1}, the CC equaled 69 %, and the rate of fuel consumed by the fire was 93 t ha^{-1}. Note that data for the measurements conducted in Mexico (FC rate of 17 t ha^{-1}) were not included to calculate these biome averages, because no FL and CC values were provided in that study. Moreover, we only focused on measurements that represent a total FC rate, including ground, surface and crown fuels (Table 1c, indicated in bold). Studies that present information on one specific fuel class (e.g. ground fuels (Goodrick et al., 2010)) were excluded in the biome average calculations. Although FL for North America, Australia and Tasmania were comparable (∼ 161 t ha^{-1}), the FC rates showed some discrepancies with higher values for North America (118 t ha^{-1}) compared to Australia and Tasmania (78 t ha^{-1}). One of possible causes of this discrepancy is the contribution of different vegetation types, as elaborated in Fig. 4. Measurements in North America were mainly conducted in conifer forest, while eucalypt was the more dominant forest type for Australia and Tasmania. FC rates for both forest types compare fairly well with the regional averages found, and equaled 109 t ha^{-1} for conifers and 79 t ha^{-1} for eucalypt forest.

Table 2c shows that litter in the temperate forest had a higher FL and FC rate than in the tropical forest biome, and the average FC for this surface fuel category equaled 17 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 %), while the fraction of rotten woody debris consumed by the fire was very high (96 %), resulting in an average FC of 20 t ha^{-1} for this category. The most important fuel category from a FC perspective was duff, with an average rate of 42 t ha^{-1}. For the same reasons as explained in Sect. 2.1, the total FL sum of different fuel categories (127 t ha^{-1}) was lower than the biome average

(161 t ha^{-1}). On the other hand, FC rates compared well with 94 t ha^{-1} and 93 t ha^{-1} for the total sum and biome average, respectively.

2.4 Boreal forest

The fire regimes in the boreal forest are thought to be mostly natural due to the vast size of the forest region, the low population densities and the difficult accessibility. 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 taken between 1973 and 2007 and were almost all conducted in boreal North America (35 in total), except for three measurement sets that came from boreal Asia (Fig. 1, Table 1d). The general method for determining FL and FC was to apply the planar intersect modeling to estimate the pre-fire FL in different plots on the test site. Post-fire, the fuels were gathered and oven dried to determine FC. 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 108 $t\,ha^{-1}$, thereby substantially lower than the average FL for the temperate forests. The average CC was 47 %, and the FC equaled 39 $t\,ha^{-1}$. As for the temperate forest biome, these biome-averaged values should be taken with caution since we only used studies that presented a total FC rate based on ground, surface and crown fuels (Table 1d, indicated in bold). However, many other studies provided data for specific fuel classes only (ground fuels: e.g. Kane et al., 2007; surface fuels: e.g. de Groot et al., 2007). These were thus excluded to calculate biome averages, but used for fuel category specific information as presented in Table 2d. Differences between boreal North America and Siberia were observed, but it should be noted that only one study (out of 3) provided a total FC estimate for Russia (FIRESCAN Science Team, 1996). Values on FL, CC, and FC were overall higher for boreal fires in North America than the field study in Russia (Fig. 5).

Information on fuel categories is presented in Table 2d, as well as in Fig. 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 Sect. 3.4). The highest FL (50 $t\,ha^{-1}$) and FC rates (32 $t\,ha^{-1}$) in the boreal forest biome were 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, different facing slopes in Alaska showed 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 (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 the burning of crop residues (Sect. 2.6) and pasture burning. The latter type of burning often follows tropical primary forest 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 7 unique measurement locations and cover 4 different continents (Fig. 1). Note that two studies represent shifting cultivation measurements and were not included in the biome average calculation. Pasture had an average FL, CC, and FC of 74 t ha^{-1}, 47 %, and 28 t ha^{-1}, respectively. Regional discrepancies for FC were found though, with FL for Brazilian pastures (84 t ha^{-1}) being substantially higher than found in Mexico (35 t ha^{-1}). However, FC rates compared reasonably well for both regions (30 and 24 t ha^{-1} for Brazil and Mexico, respectively). 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 in Zambia (43 t ha^{-1}: Stromgaard, 1985). Due to the relatively small number of measurements, these findings are not conclusive.

2.6 Crop residue

Crop residue burning is a common practice to control pests, diseases, weeds and 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.). The fires are also started in various ways, ranging from back burns, flanking fires and point source ignitions, ignited with burning old tractor tires, gasoline or flamethrowers. Detecting these fires using global burned area products is difficult as in general cropland fires are small and 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). The traditional methods in the scientific literature have been to obtain estimates for agricultural fires are by using governmental statistics on crop yield, residue usage for cooking and livestock (the leftovers are assumed to be burned), field measurements, or by using agronomic data (e.g. Jenkins et al., 1992).

Measurements conducted in the crop residue biome were taken between the 1980's and 2010 (Table 1f). On average, crop residue burning had a FL of 8.3 $\mathrm{t\,ha^{-1}}$, CC of 75 % and FC rate of 6.5 $\mathrm{t\,ha^{-1}}$. We estimated an average FL of 23 $\mathrm{t\,ha^{-1}}$ for Brazilian sugarcane (Lara et al., 2005) by using a CC of 88 % as reported by McCarty et al. (2011). FC rates for different US crop types (McCarty et al., 2011) were based on FL data from 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 0.65 for cotton and sugarcane and 0.85 for wheat and bluegrass, which are in good agreement with the CC value used by the Environmental Protection Agency (EPA) of 0.88 (EPA 2008 GHG).

FC rates varied wildly between different crop types, as shown in Fig. 6. For US crops the highest FC rates were 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 substantially lower. In general, US crop values are more or less representative for other developed agricultural areas like Brazil and Russia, but uncertainty increases for less industrialized agricultural areas in for example Africa and Asia. However, Brazilian sugarcane (20 t ha^{-1}) was found to have a FC rate 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.

2.7 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 4 different measurement locations in southwestern US (Table 1, Fig. 1g). Since Cofer III et al. (1988) only provided a FC rate for chaparral burning, we used a CC of 78 % from Hardy et al. (1996) to estimate a biome average FL of 39 t ha^{-1}. The CC equaled 78 %, yielding an average FC of 31.5 t ha^{-1}. Comparing a young and a mature chamise (evergreen chaparral shrub), similar values were found for FL (~ 20.5 t ha^{-1}) of and the same counts for their FC rates (15.5 t ha^{-1}).

2.8 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 South East 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 surface layer can burn as long as it is not waterlogged. 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 $\mathrm{g\,cm^{-3}}$ and the carbon content (although more variable) ranges between 56–58 % (Page et al., 2002; Riely et al., 2008; Ballhorn et al., 2009). 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 depth of drainage and drought on one hand and depth of burning on the other (Ballhorn et al., 2009). Commercial logging over the last decades has drained the peat swamps and forests in much of Indonesia, resulting in a greater vulnerability to fire, especially during droughts (such as during an ENSO event).

In total 4 studies provided data on tropical peatland measurements in Indonesia, conducted between 1997 and 2006 (Table 1h). There were multiple plots per study site and from each plot the pre-fire FL was determined by taking peat samples at various depths to determine the density. After the fire, information on peat carbon content and the average burn depth was then combined to determine the FC. The tropical peat fire regime had the highest FC of all biomes, with an average rate of 314 $\mathrm{t\,ha^{-1}}$. 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 $\mathrm{t\,ha^{-1}}$, 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.

2.9 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 peat fires to fire during different moisture conditions is poorly documented at best. This makes modeling peat fires very difficult and stresses the importance of field measurements and paleoecological studies.

Two measurements were taken between 1999 and 2001 in boreal Canada (Table 1i). On each burn site, multiple plots were established and the peat depth was sampled to determine the peat density. After the burn the bulk density 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 both studies is 42.5 t ha^{-1}. Turetsky and Wieder (2001) showed that FC of permafrost bogs (57.5 t ha^{-1}) is more than twice as high as continental bogs (26.5 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 t ha^{-1}, while fires in hollows consumed on average 56 t ha^{-1} (Benscoter and Wieder, 2003).

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2.10 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 storage 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, evidence of increasing fire frequency and larger extent of the fires in the arctic 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 t ha^{-1}, and averaged CC and total FC was respectively 24 % and 40 t ha^{-1} (Table 1j). 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 good field measurements in 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 rates measured in the field

Due to the spatial heterogeneity in fire occurrence 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 rates 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 (Fig. 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 in not now but may be of consequence 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 Figs. 2–5. For example, we found substantial differences in FL and FC rates for boreal areas, with Russian sites having lower values compared to the ones in North America (Fig. 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). Available literature data showed that FC rates for crown fuels were indeed higher than for surface fuels, but due to the overall large contribution of forest floor 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 vs. late dry season) contribute to different boreal FC rates as well.

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. South East 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 FL than forests in the Amazon and Indonesia (Fig. 3), and had higher FC rates as well. Different forest types can likely explain this difference; in Fig. 3 substantial differences are shown for FL, CC, and FC in primary tropical evergreen forest, tropical evergreen second-growth 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 the regional discrepancies found 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 extreme care should be taken with using biome-average values. They provide a guideline but it is probably more useful to continue developing models that aim to account for variability within biomes, and use the database to constrain these models, rather than to simply use biome-average values. Use of FC rates for specific vegetation types (like crops as presented in Fig. 6) or fuel categories offers an interesting alternative, and is further discussed in Sect. 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 FRP-derived studies (Sect. 3.3). GFED3 fire emissions estimates 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 rates we divided the GFED3 total biome-specific emissions estimates (g Dry Matter) in every grid cell by the total burned area observed for every grid cell. Since biome-specific information on the area burned within one pixel was not available, we assumed that for every pixel the burned area followed the same fractionation as the GFED3 emissions estimates. For certain regions and time periods however, this may over- or underestimate biome-averaged FC rates. In Table 3 an overview is given for biome-specific FL, CC, and FC rates that we estimated from data found in literature. 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) and the whole biome (second number), and the sixth column presents the difference between GFED3 FC and the rates measured in the field.

In general, the average FC rates agreed reasonably well, with differences between GFED3 and the field measurements of +10, +2, −14, and −27 % for boreal forest, pasture, crop residue and boreal peat, respectively. However, for certain biomes much larger discrepancies (> 70 %) were found, and 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 field rates by 72 %, and this overestimation was even higher for grassland regions (79 %). 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). When focusing on the GFED FC average for the whole grassland biome (6.3 t ha^{-1}) instead of the collocated grid cells only (7.7 t ha^{-1}), the overestimation was lower (50 %) but still large. This emphasizes the difficulty in converting very localized field measurements into regional FC values. Improved resolution for the models will help to alleviate this problem and bring model values closer to the field measurements.

For tropical forests, an important biome due to large-scale deforestation emissions, substantial differences were found as well: GFED3 overestimated FC rates by 70 % 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 (Morton et al., 2008) were modeled by GFED 3 while these are not included in the field measurements. Given the large difference between FC rates for collocated grid cells (215 t ha^{-1}) and the whole biome (44 t ha^{-1}), we can infer that the field measurement locations were biased towards high intensity deforestation events. Clearly, as discussed in Sect. 3.1, regional differences found within the biome play an important role here: 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 (Fig. 3).

In the temperate forest biome FC was underestimated in GFED3 by 62 % compared to the field measurement average for collocated grid cells. In our averaged field measurement estimate we focused on studies that provided a total FC rate (i.e. the FC rate of ground, surface and/or crown fuels), thereby excluding studies that only measured one specific fuel class (e.g. ground fuels). It remains uncertain though whether these “total” FC rates measured during prescribed burns are representative for wildfires. By including studies that only measured FC for ground fuels, the field average would be lower as well as the discrepancy with GFED3. This issue also counts for boreal forests, where the contribution of ground fuels to total FC is often even larger than for the temperate forest biome. Uncertainties in FC rates for belowground biomass are substantial though, since these are difficult to measure and therefore not always fully taken into account by studies.

For most biomes, a few field measurements had a FC rate 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 Fig. 4). By neglecting these outliers the biome-averaged values may change significantly: e.g. excluding the high FC rate of 299 $\mathrm{t\,ha^{-1}}$ found for a temperate forest in Tasmania (Hollis et al., 2010) would lower the biome-averaged FC rate from 91 $\mathrm{t\,ha^{-1}}$ to 76 $\mathrm{t\,ha^{-1}}$, thereby decreasing the difference between GFED3 and the field measurement outcomes from 62 % to 54 %. The large difference between the GFED3 FC average for collocated grid cells (35 $\mathrm{t\,ha^{-1}}$) and the whole biome (1.6 $\mathrm{t\,ha^{-1}}$) clearly indicates that the measurement locations shown in Table 1 were not representative for the whole temperate forest biome. The same counts for crop residues: GFED3 underestimated FC field rates by 14 % for the collocated grid cells, but compared to the whole biome a larger underestimation of 82 % was found. Since regional differences are likely to be large and not much field data is available, croplands deserve special attention in future measurements campaigns.

Finally, we note that biome-averaged values presented in this paper were based on the studies shown and cited in the different tables, and cover all available measurements on FC. However, additional studies on FL measurements exist for different biomes, especially for southern Africa and Australia. These FL data were not included here, but listed in a spreadsheet that is available online at http://www.falw.vu/~gwerf/fuel_consumption/. Including these additional field measurements may change the regional FL averages that are presented in this study.

3.3 Field measurement averages and comparison with FRP derived FC estimates

Besides a comparison with GFED3 data, we performed a comparison of field measurement averages with FRP-derived estimates as well. The basis of the FRP approach for estimating FC is that the heat content of vegetation is more or less constant, and that the fire radiative energy (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 kg MJ^{-1} across of a range of fuels burned in laboratory conditions (Wooster et al., 2005). More recent experiments under field conditions by Kumar et al. (2011) and Schroeder et al. (2014) indicated a slightly lower conversion factor of 0.313 kg MJ^{-1} and 0.261 kg MJ^{-1}, respectively, for grasslands in North America. Schroeder et al. (2014) also highlighted that correction for atmospheric disturbances may significantly alter FRP retrievals and hence estimates of FC.

There is a number of studies that relate FRP 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 FRP to operationally assess air pollution through biomass burning. 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. Hence, evidence of performance of FRP-based methods against field experiments is more of an anecdotal nature.

A common finding of FRP-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 a range of land cover types in the savanna biome a median FC rate of ∼ 4 t ha^{-1} was found for grassland and shrubland, while the median for woodland was ∼ 5 t ha^{-1}. This corresponds relatively well with the mean of 4.3 t ha^{-1} and 5.1 t ha^{-1} found here in grassland and woodland field studies, 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 and estimated a FC rate of about 4 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 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 FRP seems to provide realistic estimates under a range of conditions, issues of undersampling of FRP and – maybe less important – the conversion of FRP/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 rates for different fuel categories

As discussed in Sect. 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 rates 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. 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 rates. Another biome that deserves more attention in future studies is crop residue, since our understanding of FC rate variability for different crop types is still poor.

4 Summary

This study aimed to compile all peer-reviewed literature on measured fuel consumption rates in landscape fires. The field measurements were partitioned into 10 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 121 unique measurement locations. The biome-averages and fuel type specific data of fuel load and fuel consumption rates 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 reasonable well with the 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 rates becomes available, the field measurement database will be updated. The most up-to-date version can be retrieved from http://www.falw.vu/~gwerf/fuel_consumption/. 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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Table 1. Location, fuel load (FL), combustion completeness (CC) and fuel consumption (FC) for field measurements conducted in the savanna **(a)**, tropical forest **(b)**, temperate forest **(c)**, boreal forest **(d)**, pasture **(e)**, crop residue **(f)**, chaparral **(g)**, tropical peat **(h)**, boreal peat **(i)**, and tundra biome **(j)**. 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 (°)	Lon (°)	Location	FL ($t\,ha^{-1}$)	CC (%)	FC ($t\,ha^{-1}$)	Note
1	25.15 S	31.14 E	Kruger Park, South Africa	**4.4 (1.4)**	**80 (16)**	**3.5 (1.4)**	Lowveld sour bushveld savanna
1	12.35 S	30.21 E	Kasanka National Park, Zambia	**5.4 (2.1)**	**81 (15)**	**4.2 (1.0)**	Dambo, Miombo, Chitemene
1	16.60 S	27.15 E	Choma, Zambia	**5.1 (0.4)**	**88 (2)**	**4.5 (–)**	Semi-arid Miombo
2	14.52 S	24.49 E	Kaoma Local Forest, Zambia	**5.8 (3.8)**	**53 (32)**	**2.2 (1.2)**	Dambo and Miombo
3	15.00 S	23.00 E	Mongu region, Zambia	**4.2 (0.8)**	**69 (21)**	**2.9 (0.9)**	Dambo and Floodplain
4	12.22 N	2.70 W	Tiogo state forest, Senegal	**5.8 (1.6)**	**75 (15)**	**4.2 (0.7)**	Grazing and No grazing
5	15.84 S	47.95 W	Brasilia, Brazil	**8.3 (1.3)**	**88 (13)**	**7.2 (0.9)**	Different types of Cerrado
6	8.56 N	67.25 W	Calaboza, Venezuela	**6.9 (2.3)**	**82 (17)**	**5.5 (1.9)**	Protected savanna for 27 years
7	15.51 S	47.53 W	Brasilia, Brazil	**8.3 (–)**	**90 (–)**	**7.5 (–)**	Campo limpo and Campo sujo
8	15.84 S	47.95 W	Brasilia, Brazil	**8.9 (3.1)**	**92 (4.1)**	**8.2 (2.8)**	Different types of Cerrado
9	3.75 N	60.50 W	Roraima, Brazil	**6.1 (3.6)**	**56 (27)**	**2.6 (0.9)**	Different types of Cerrado
10	12.40 S	132.50 E	Kapalga, Kakadu, Australia	**4.8 (1.3)**	**94 (0.6)**	**4.5 (1.3)**	Woodland
11	12.30 S	133.00 E	Kakadu National Park, Australia	**5.6 (0.9)**	**91 (–)**	**5.1 (–)**	Tropical savanna
12	12.43 S	131.49 E	Wildman Reserve, Australia	**2.9 (1.8)**	**91 (14)**	**2.4 (1.1)**	Grass and Woody litter
13	12.38 S	133.55 E	Arnhem plateau, Australia	**3.6 (3.1)**	**44 (35)**	**1.4 (1.6)**	Early and Late season fires
14	12.38 S	133.55 E	Arnhem plateau, Australia	**8.5 (–)**	**39 (–)**	**4.8 (–)**	Grass and Open Woodland
15	17.65 N	81.75 E	Kortha Valasa and Kudura, India	**35 (6.4)**	**22 (7.7)**	**7.7 (2.6)**	Woodland

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Table 1b. Tropical forest.

Ref[a]	Lat (°)	Lon (°)	Location	FL $(\mathrm{t\,ha^{-1}})$	CC (%)	FC $(\mathrm{t\,ha^{-1}})$	Note
5	4.30 S	49.03 W	Marabá, Pará, Brazil	**207 (–)**	**48 (–)**	**103 (–)**	Primary and Secondary forest
16	2.29 S	60.09 W	Fazenda Dimona, Manaus, Brazil	**265 (–)**	**29 (–)**	**77 (–)**	200 ha clearing for pasture
17	7.98 S	38.32 W	Serra Talh., Pernambuco, Brazil	**74 (0.2)**	**87 (8.6)**	**64 (6.3)**	Second-growth tropical dry forest
18	4.50 S	49.01 W	Marabá, Pará, Brazil	**364 (–)**	**52 (–)**	**190 (–)**	Cleared for pastures
18	15.85 S	60.52 W	Santa Barbara, Rondônia, Brazil	**326 (–)**	**50 (–)**	**166 (–)**	Cleared for shifting cultivation
19	2.61 S	60.17 W	Manaus, Brazil	**425 (–)**	**25 (–)**	**107 (–)**	Tropical dense rainforest
20	9.11 S	63.16 W	Jamari, Rondônia, Brazil	**377 (31)**	**50 (4.5)**	**191 (33)**	Primary forest slash
21	2.61 S	60.17 W	Manaus, Brazil	**402 (–)**	**20 (–)**	**82 (–)**	Humid dense tropical forest
22	10.16 S	60.81 W	Ariguimes, Rondônia, Brazil	**307 (49)**	**36 (–)**	**110 (–)**	Open tropical forest
23	3.37 S	52.62 W	Altamira, Pará, Brazil	**263 (–)**	**42 (–)**	**110 (–)**	Lowland Amazonian dense forest
24	2.50 S	48.12 W	Igarape do vinagre, Pará, Brazil	**214 (–)**	**20 (–)**	**43 (–)**	Tropical dense rainforest
25	5.35 S	49.15 W	Djair, Pará, Brazil	**121 (17)**	**43 (–)**	**52 (–)**	Slashed Second-growth forest
25	9.20 S	60.50 W	Rondônia, Brazil	**118 (45)**	**56 (7.7)**	**65 (21)**	Second, Third-growth forest
25	4.30 S	49.03 W	José, Pará, Brazil	**64 (4.0)**	**87 (–)**	**55 (–)**	Third-growth forest
26	2.34 S	60.09 W	Fazenda dimona, Manaus, Brazil	**369 (187)**	**30 (–)**	**111 (–)**	Lowland Amazonian dense forest
27	9.52 S	56.06 W	Alta floresta, Mato Grosso, Brazil	**496 (–)**	**39 (18)**	**192 (87)**	1, 4, and 9 ha clearings
28	9.97 S	56.34 W	Alta floresta, Mato Grosso, Brazil	**306 (–)**	**24 (–)**	**73 (–)**	Primary forest, 4 ha
29	12.53 S	54.88 W	Feliz Natal, Mato Grosso, Brazil	**219 (–)**	**71 (–)**	**155 (–)**	Seasonal semi-deciduous forest
30	7.90 S	72.44 W	Cruzeiro do Sul, Acre, Brazil	**583 (–)**	**39 (–)**	**226 (–)**	Primary forest, 4 ha clearing
31	18.35 N	95.05 W	Los Tuxtlas, Mexico	**403 (–)**	**95 (–)**	**380 (–)**	Evergreen tropical forest
32	19.30 N	105.3 W	San Mateo, Jalisco, Mexico	**127 (–)**	**71 (–)**	**91 (–)**	Tropical dry forest
33	0.52 S	117.01 E	East-Kalimantan, Indonesia	**237 (106)**	**56 (24)**	**120 (47)**	Lightly and Heavily disturbed stands

Table 1c. Temperate forest.

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

Table 1d. Boreal forest.

Ref[a]	Lat (°)	Lon (°)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
44	46.98 N	83.43 W	Aubinadong River, ON, Canada	**99 (4.2)**	**66 (5.4)**	**34 (6.6)**	Different depth classes used
45	46.78 N	83.33 W	Sharpsand Creek, ON, Canada	**48 (10)**	**49 (18)**	**23 (7.6)**	Immature jack pine
46	48.92 N	85.29 W	Kenshoe Lake, ON, Canada	**332 (–)**	**7.5 (–)**	**24 (–)**	Surface and Crown
47	63.38 N	158.25 W	Innoko, Alaska, USA	–	–	**37 (7.0)**	Black spruce forest/shrub/bog
48	64.45 N	148.05 W	Rosie Creek, Alaska, USA	–	–	83	Ground fuels
48	60.43 N	149.17 W	Granite Creek, Alaska, USA	–	–	30	Ground fuels
48	67.14 N	150.18 W	Porcupine, Alaska, USA	–	–	25	Ground fuels
48	63.12 N	143.59 W	Tok River, Alaska, USA	–	–	51	Ground fuels
48	63.45 N	145.12 W	Dry Creek, Alaska, USA	–	–	41	Ground fuels
48	63.08 N	142.30 W	Tetlin, Alaska, USA	–	–	56	Ground fuels
48	63.50 N	145.15 W	Hajdukovich Creek, Alaska, USA	–	–	129	Ground fuels
49	61.60 N	117.20 W	Fort Providence, NT, Canada	**83 (10)**	**44 (7.6)**	**36 (5.8)**	Jack pine and black spruce
50	65.10 N	147.30 W	Alaska, USA	–	–	19 (1.7)	Forest floor
51	64.40 N	145.74 W	Delta Junction, Alaska, USA	75 (–)	48 (–)	35 (–)	Ground fuels: (non)-permafrost
52	53.92 N	105.70 W	Montreal Lake, SK, Canada	43 (4.0)	62 (7.7)	27 (3.9)	Spruce, Pine, Mixed wood
53	65.03 N	147.85 W	Fairbanks, Alaska, USA	95 (17)	61 (17)	57 (19)	Different facing slopes
54	46.87 N	83.33 W	Sharpsand Creek, ON, Canada	13 (2.0)	69 (32)	9 (4.0)	Experimental fire: forest floor
54	48.87 N	85.28 W	Kenshoe Lake, ON, Canada	17 (3.0)	35 (13)	6 (2.0)	Experimental fire: forest floor
54	61.37 N	117.63 W	Fort Providence, NT, Canada	47 (9.0)	36 (9.0)	17 (3.0)	Experimental fire: forest floor
54	61.69 N	107.94 W	Porter Lake, NT, Canada	15 (0.0)	60 (20)	9 (3.0)	Experimental fire: forest floor
54	55.07 N	114.03 W	Hondo, AB, Canada	3 (1.0)	33 (35)	1 (1.0)	Experimental fire: forest floor
54	59.31 N	111.02 W	Darwin Lake, NT, Canada	18 (3)	72 (20)	13 (3.0)	Experimental fire: forest floor
54	55.74 N	97.91 W	Burntwood River, MB, Canada	72 (12)	26 (8.0)	19 (5.0)	Wildfire: forest floor
54	54.29 N	107.78 W	Green Lake, SK, Canada	36 (13)	86 (54)	31 (16)	Wildfire: forest floor
54	53.57 N	88.62 W	Kasabonika, ON, Canada	69 (19)	55 (46)	38 (30)	Wildfire: forest floor
54	55.74 N	97.85 W	Thompson, MB, Canada	23 (14)	87 (63)	20 (8.0)	Wildfire: forest floor
54	54.05 N	105.81 W	Montreal Lake, SK, Canada	61 (41)	57 (47)	35 (17)	Wildfire: forest floor
54	64.06 N	139.43 W	Dawson City, YT, Canada	84 (30)	46 (31)	39 (22)	Wildfire: forest floor
54	59.40 N	113.03 W	Wood Buffalo Nat. Pk., Canada	37 (9.0)	59 (35)	22 (12)	Wildfire: forest floor
55	60.49 N	150.98 W	Soldotna, Alaska, USA	**91 (22)**	**37 (5.2)**	**33 (4.4)**	Mystery creek 1–3
55	61.61 N	149.04 W	Palmer, Alaska, USA	**84 (4.2)**	**61 (3.5)**	**51 (5.7)**	Deshka 1–2
55	62.69 N	141.77 W	Tetlin Refuge, Alaska, USA	**105 (16)**	**45 (15)**	**49 (20)**	Tetlin, Chisana 1–4
55	64.87 N	147.71 W	Fairbanks, Alaska, USA	**86 (17)**	**37 (22)**	**32 (22)**	Bonanza Creek, Frostfire
56	63.00 N	142.00 W	Alaska, USA	**152 (–)**	**59 (–)**	**90 (–)**	Black spruce forest
57	65.00 N	146.00 W	Alaska, USA	**72 (–)**	**58 (–)**	**40 (–)**	Black spruce forest
58	60.45 N	89.25 E	Bor, Krasnoyarsk, Russia	**34 (–)**	**50 (–)**	**17 (–)**	Pine-lichen forest and litter
59	58.58 N	98.92 E	Lower Angara, Russia	54 (12)	31 (15)	17 (8.6)	Scots pine, Larch mixed-wood
59	58.70 N	98.42 E	Lower Angara, Russia	43 (–)	42 (–)	18 (–)	Scots pine, Larch mixed-wood

Table 1e. Pasture.

Ref[a]	Lat (°)	Lon (°)	Location	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	Note
60	10.53 S	31.14 E	Kasama, Zambia	75 (–)	64 (–)	43 (–)	Shifting cultivation
20	9.17 S	63.18 W	Jamari, Rondônia, Brazil	**66 (13)**	**31 (10)**	**21 (17)**	12 year old pasture site
61	5.30 S	49.15 W	Fransico, Pará, Brazil	**53 (4.8)**	**83 (–)**	**44 (–)**	2 slash fires prior to burning
61	9.20 S	60.50 W	João and Durval, Rondônia, Brazil	**96 (–)**	**34 (–)**	**30 (–)**	4 year old pasture site
62	2.54 N	61.28 W	Vila de Apiau, Roraíma, Brazil	**119 (–)**	**20 (–)**	**24 (–)**	Pasture and Forest
32	19.30 N	105.3 W	San Mateo, Jalisco, Mexico	**35 (–)**	**69 (–)**	**23 (–)**	High and Low severity
63	17.59 N	81.55 E	Damanapalli and Velegapalli, India	14 (–)	30 (–)	4 (–)	Shifting cultivation in Dry forest

Table 1f. Crop residue.

Ref[a]	Lat (°)	Lon (°)	Location	FL ($t\,ha^{-1}$)	CC (%)	FC ($t\,ha^{-1}$)	Note
64	40.00 N	2.00 W	Spain, Europe	**1.4 (–)**	**80 (–)**	**1.1 (–)**	Cereal crops
65	22.85 S	47.60 W	Piracicaba, Sao Paulo, Brazil	–	–	**20 (–)**	Sugar cane
66	33.94 N	118.33 E	Suqian, China	**6.7 (1.2)**	**44 (4.6)**	**2.9 (0.5)**	Mix (wheat, rice, corn, potato)
67	40.00 N	98.00 E	North America	**2.4 (3.6)**	**0.9 (0.1)**	**2.1 (3.2)**	Mix of crop types
67	46.73 N	117.18 E	North America	**12 (–)**	**90 (–)**	**11 (–)**	Seedgrass

Table 1g. Chaparral.

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

Table 1h. Tropical peat.

Ref[a]	Lat (°)	Lon (°)	Location	FL ($\mathrm{t\,ha^{-1}}$)	CC (%)	FC ($\mathrm{t\,ha^{-1}}$)	Note
70	2.52 S	113.79 E	Kalimantan, Indonesia	–	–	**500 (–)**	Peat and Overstory
71	2.50 S	114.17 E	Palangka Raya, Indonesia	**399 (11)**	**27 (4.7)**	**109 (19)**	Various peat fire fuels
72	2.37 S	102.68 E	Pelawan, Riau, Indonesia	45 (6.1)	81 (10)	37 (8.2)	Litter and Branches
73	2.52 S	113.79 E	Kalimantan, Indonesia	–	–	**332 (6.4)**	Measured by LIDAR

Table 1i. Boreal peat.

Ref[a]	Lat (°)	Lon (°)	Location	FL ($t\,ha^{-1}$)	CC (%)	FC ($t\,ha^{-1}$)	Note
74	55.85 N	107.67 W	Patuanak, Canada	–	–	**42 (25)**	Continental and Permafrost bogs
75	54.93 N	114.17 W	Chisholm, Canada	–	–	**43 (–)**	Hummocks and hollows

Table 1j. Tundra.

Ref[a]	Lat (°)	Lon (°)	Location	FL ($t\,ha^{-1}$)	CC (%)	FC ($t\,ha^{-1}$)	Note
76	68.58 N	149.72 W	Anaktuvuk River, Alaska, USA	**165 (15)**	**24 (5.0)**	**40 (9.0)**	Soil and 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 Jr. et al. (2014); (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) Hollis et al. (2010); (43) Yokelson et al. (2007); (44) Stocks et al. (1987a); (45) Stocks et al. (1987b); (46) Stocks (1989); (47) Goode et al. (2000); (48) Kasischke et al. (2000); (49) Stocks et al., 2004; (50) Harden et al. (2004); (51) Harden et al. (2006); (52) de Groot et al. (2007); (53) Kane et al. (2007); (54) de Groot et al. (2009); (55) Ottmar and Sandberg (2010); (56) Turetsky et al. (2011); (57) Boby et al. (2010); (58) FIRESCAN Science Team (1996); (59) Ivanova et al. (2011); (60) Stromgaard, 1985; (61) Kauffman et al. (1998); (62) Barbosa and Fearnside (1996); (63) Prasad et al. (2000); (64) Zarate et al. (2005); (65) Lara et al. (2005); (66) Yang et al. (2008) ; (67) McCarty et al. (2011); (68) Cofer III et al. (1988); (69) Hardy et al. (1996); (70) Page et al. (2002); (71) Usup et al. (2004); (72) Saharjo and Nurhayati (2006); (73) Ballhorn et al. (2009); (74) Turetsky and Wieder (2001); (75) Benscoter and Wieder (2003); (76) 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 **(a)**, tropical forest **(b)**, temperate forest **(c)**, and boreal forest biome **(d)**. Standard deviation (SD) is shown in parenthesis.

Table 2a. Savanna.

CI[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 (0–0.64 cm)	0.6 (0.7)	65 (16)	0.4 (0.5)	1, 2, 5, 8
S	Woody debris (0.64–2.54 cm)	0.9 (1.0)	39 (25)	0.5 (0.7)	1, 2, 5, 8
S	Woody debris (> 2.54 cm)	1.0 (1.1)	21 (12)	0.3 (0.3)	1, 2, 5, 8

Table 2b. Tropical forest.

CI[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
S	Logs (> 30 cm) and Trunks	198 (50)	17 (17)	31 (25)	16, 19, 21, 22, 23, 26, 27, 28, 29, 30
G	Rootmat	5.2 (2.7)	87 (13)	4.4 (2.2)	18, 20, 25
S	Woody debris (0–0.64 cm)	4.6 (2.8)	94 (4.8)	6.4 (8.6)	5, 17, 18, 20, 25, 32
S	Woody debris (0.65–2.54 cm)	17 (3.9)	87 (7.9)	15 (4.0)	5, 17, 18, 20, 25, 32
S	Woody debris (2.55–7.6 cm)	27 (15)	65 (19)	18 (13)	5, 17, 18, 20, 25, 32
S	Woody debris (7.6–20.5 cm)	45 (29)	41 (18)	18 (9.3)	5, 17, 18, 20, 25, 32
S	Woody debris (> 20.5 cm)	91 (87)	45 (19)	37 (40)	5, 18, 20, 25, 32

Table 2c. Temperate forest.

CI[a]	Fuel category	FL (t ha^{-1})	CC (%)	FC (t ha^{-1})	References[b]
G	Duff	58 (40)	60 (44)	42 (39)	34, 37, 38
S	Litter	20 (11)	81 (8.9)	17 (9.9)	34, 37, 38
S	Woody debris (0–0.64 cm)	1.2 (0.8)	87 (11)	1.0 (0.6)	36, 37, 38
S	Woody debris (0.65–2.54 cm)	5.2 (1.9)	79 (11)	4.0 (1.2)	36, 37, 38
S	Woody debris (2.55–7.6 cm)	6.0 (0.9)	73 (14)	4.3 (0.2)	36, 37, 38
S	Woody debris (7.6–20.5 cm sound)	16 (9.6)	38 (42)	6.2 (8.2)	36, 37, 38
G	Woody debris (7.6–20.5 cm 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 Jr. et al. (2014); (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); (44) Stocks et al. (1987a); (46) Stocks (1989); (48) Kasischke et al. (2000); (49) Stocks et al. (2004); (50) Harden et al. (2004); (51) Harden et al. (2006); (52) de Groot et al. (2007); (53) Kane et al. (2007); (54) de Groot et al., 2009; (55) Ottmar and Sandberg (2010); (57) Boby et al. (2010); (58) FIRESCAN Science Team (1996); (59) 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 ($t\,ha^{-1}$)	FC_{GFED3} ($t\,ha^{-1}$)[a]	Difference (%)[b]
Savanna	7.6 (6.5)	71 (26)	4.6 (2.2)	7.9/6.9	+72/+50
Grassland	5.3 (2.0)	81 (16)	4.3 (2.2)	7.7/6.3	+79/+47
Woodland	11 (9.1)	58 (32)	5.1 (2.2)	8.1/9.3	+59/+82
Tropical Forest	285 (137)	49 (22)	126 (77)	215/44	+71/−65
Temperate Forest	161 (155)	69 (13)	93 (79)	35/1.6	−62/−98
Boreal Forest	108 (80)	47 (16)	39 (19)	43/41	+10/+5
Pasture	74 (34)	47 (27)	28 (9.3)	29/–	+2/–
Crop Residue	8.3 (9.9)[c]	75 (21)	6.5 (9.0)	5.6/1.2	−14/−82
Chaparral	39 (22)[d]	78 (4.2)	32 (19)	3.9/–	−88/–
Tropical Peatland	1056 (876)[e]	27 (–)	314 (196)	228/187	−27/−40
Boreal Peatland	–	–	42 (–)	25/–	−40/–
Tundra[f]	165 (15)	24 (5.0)	40 (9.0)	–/–	–/–

[a] FC per unit area burned according to GFED3, averaged over 1997–2009. The first number represents the FC rate for the collocated grid cells, i.e. grid cells in which field measurement were taken, and the second number corresponds to the whole biome. 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.

[b] FC_{GFED3} compared to the average FC of field measurements for collocated grid cells (first number) and whole biome (second number). Positive numbers indicate that FC_{GFED3} is higher than the average FC of field measurements.

[c] 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).

[d] We assumed an average CC of 78 % as reported in Hardy et al. (1996) to estimate FL for the study of Cofer III et al. (1988).

[e] 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).

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

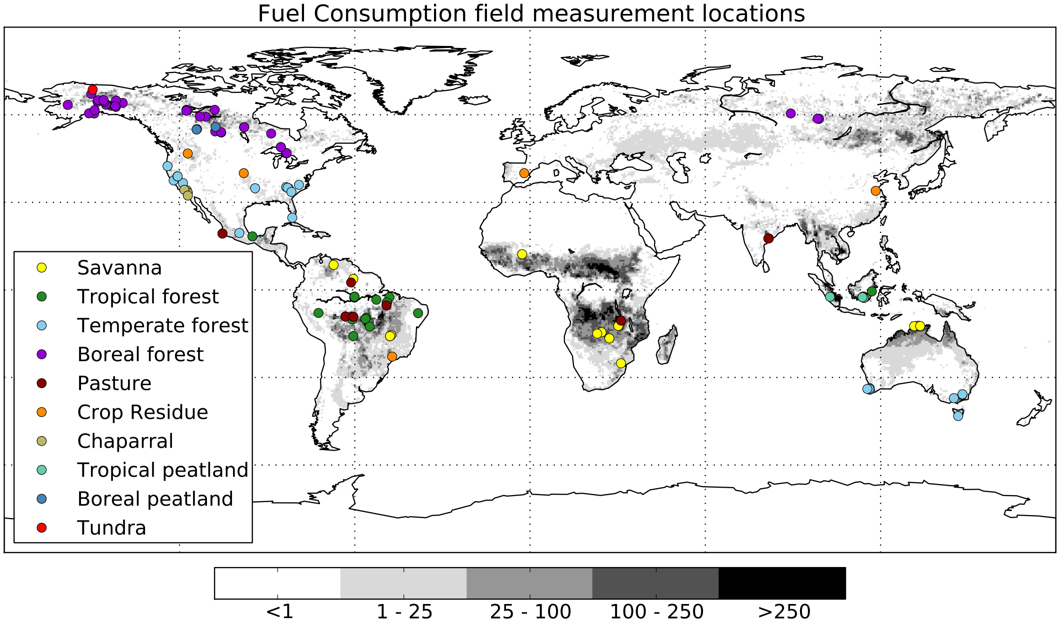

Figure 1. Fuel consumption field measurement locations for different biomes. Background map shows annual GFED3 fire C emissions in $\mathrm{g\,C\,m^{-2}\,year^{-1}}$, averaged over 1997–2009.

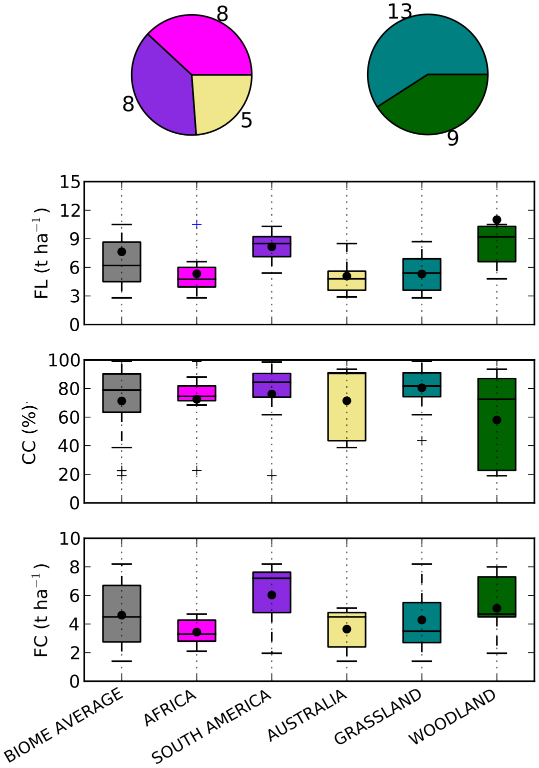

Figure 2. Overview of field measurements of fuel load (FL), combustion completeness (CC), and fuel consumption (FC) in the savanna biome. The pie charts on top correspond to the amount of unique measurement locations for different geographical regions (left) and vegetation types (right), and in the box 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.

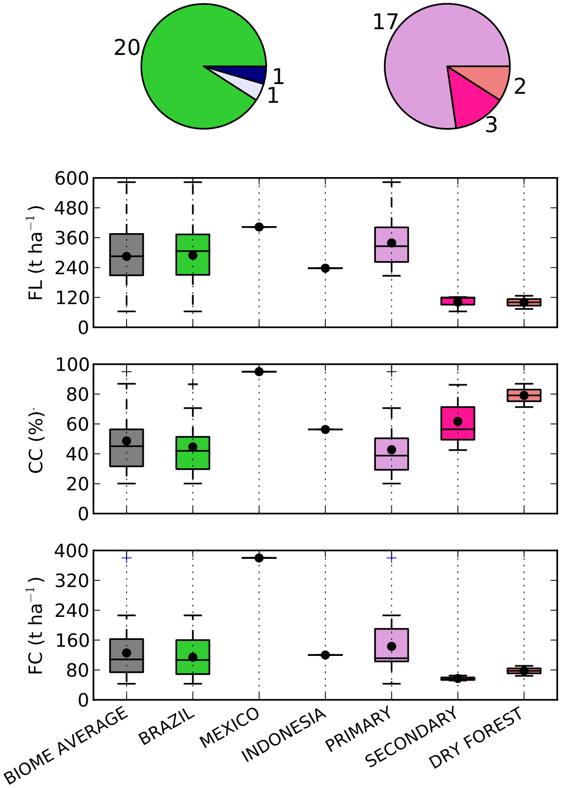

Figure 3. Overview of field measurements of fuel load (FL), combustion completeness (CC), and fuel consumption (FC) in the tropical forest biome. The pie charts on top correspond to the amount of unique measurement locations for different geographical regions (left) and forest types (right), and in the 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.

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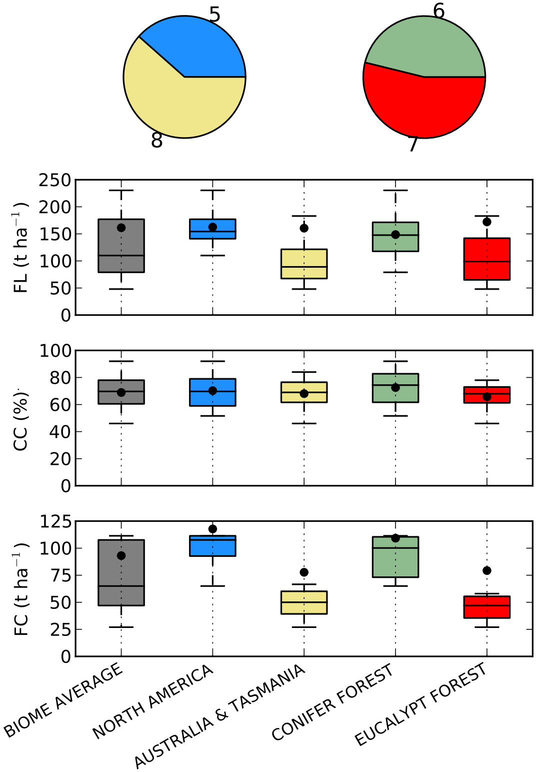

Figure 4. Overview of field measurements of fuel load (FL), combustion completeness (CC), and fuel consumption (FC) in the temperate forest biome. The pie charts on top correspond to the amount of unique measurement locations for different geographical regions (left) and forest types (right), and in 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.

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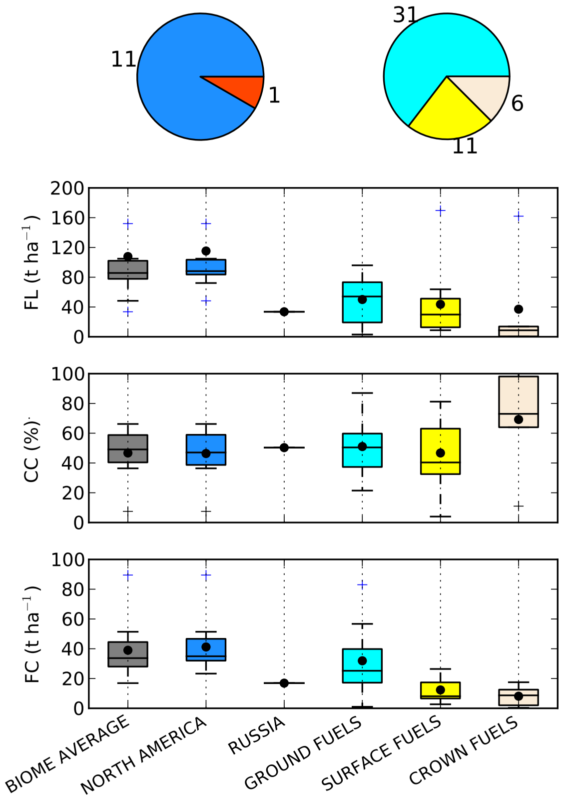

Figure 5. Overview of field measurements of fuel load (FL), combustion completeness (CC), and fuel consumption (FC) in the boreal forest biome. The pie charts on top correspond to the amount of unique measurement locations for different geographical regions (left) and fuel classes (right), and in the 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.

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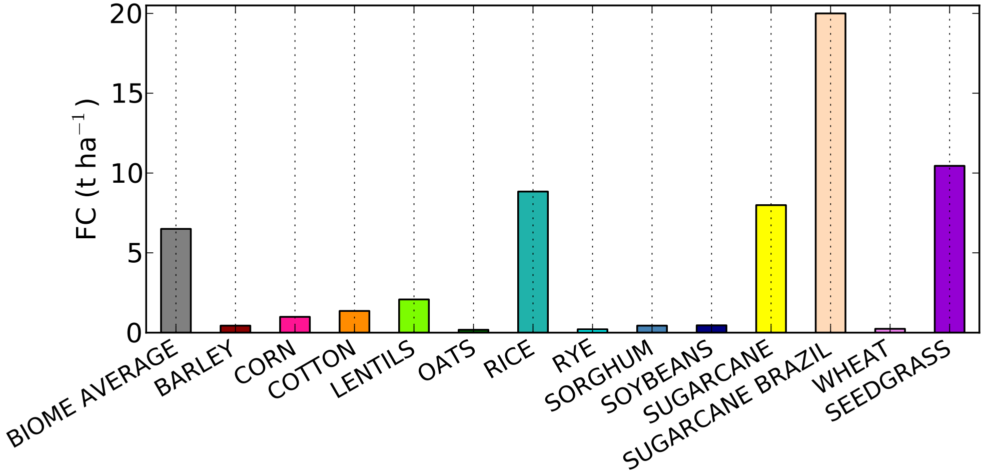

Figure 6. Fuel consumption (FC) rates for different crop types as reported by McCarty et al. (2011) and Lara et al. (2005). The grey bar corresponds to the biome-averaged FC value for crop residue burning as presented in this study.