Review of “Biomass burning fuel consumption dynamics in the (sub)tropics assessed from satellite” by Andela et al.

General comments

The paper presents an approach to estimate fuel consumption by combining satellite data with field data and analyzes the derived spatial patterns of fuel consumption. Burned area data from MODIS is combined with fire radiative power (FRP) data from SEVIRI and MODIS to estimate fuel consumption. This approach requires a factor to convert fire radiative energy (FRE) to burned dry matter. The authors used a standard factor reported in the literature based on laboratory measurements (e). As an alternative, the conversion factor was estimated from field data by fitting a regression between MODIS FRE and field measurements of fuel consumption. By using the standard conversion factor, the derived conversion factor and by using MODIS or SEVIRI FRP data, the authors find similar spatial patterns of fuel consumption but large differences in absolute numbers. Relations between fuel consumption, NPP and fire return intervals remarkably differ between continents.

I very much appreciate the approach of combining these different datasets. Such estimates are certainly valuable to better understand and model vegetation-fire-carbon cycle interactions. The paper is very well written.

We would like to start thanking the reviewer for his thoughtful and constructive remarks. Please see our response to the specific comments and minor remarks below. In addition, we will upload a pdf file containing the suggested textual changes in response to both reviews (using track change) and the updated figures, references to line numbers used here refer to this document.

Specific comments

One conclusion of the authors is “Moreover, satellite-derived fuel consumption estimates could be used as a reference for biogeochemical models, while providing improved insights in the underlying processes.” (p. 22, l. 16-17). Although I completely agree that satellite-derived data can help to improve process-representations in bio-geochemical models, I disagree with this conclusion. The authors present large differences in fuel consumption between the MODIS- and SEVIRI-based estimates and additional large differences in the lab-based and the field-based FRE-to-DM conversion factor. These two issues indicate large uncertainties in fuel consumption estimates.

Thus, I’m not convinced that these estimates can be used as a reference for models unless the uncertainties in fuel consumption are quantified. In my view, a major uncertainty originates from the fitted regression between MODIS FRE and field measurements of fuel consumption because only a limited set of field data is available with a limited representativeness for MODIS pixels. I think it is necessary to quantify the uncertainty of the regression (i.e. of the conversion factor) for example by bootstrapping the set of measurement point that goes into the computation of this regression. The bootstrapped distribution of conversion factors (or for example the 0.025, 0.5, and 0.975 quantiles of this distribution) can be then propagated into the computation of fuel consumption to provide spatial fields of upper and lower uncertainty estimates.

The distribution of conversion factors can be also used to test if the lab-based factor of 0.368 really differs from the derived factor or if this is a sampling issue. Such an uncertainty would make the estimate of fuel consumption much more valuable and I would accept it for benchmarking and testing biogeochemical models.

We agree that the uncertainty in the absolute fuel consumption estimates remains high. Our confidence in the spatial patterns is better because we find a reasonable comparison between the spatial patterns of SEVIRI-derived fuel consumption (observing the full diurnal cycle) and MODIS derived fuel consumption. The biggest challenge is to create accurate estimates of FRE, while SEVIRI misses much fire activity due to its large distance to Earth and subsequently large pixel size, the MODIS instruments provide only a limited number of daily observations and further suffer from increasing pixel sizes towards the swath edges. We assume that the conversion factor found by Wooster et al. (2005) is correct, and that structural differences between the uncorrected MODIS derived fuel consumption and field observations stem from errors in our FRE estimates. Following the suggestion of reviewer #2 we therefore now speak of a "FRE correction factor", rather than deriving an alternative conversion factor. Although this does not affect our fuel consumption estimates, it does provide the reader with better insight in where the largest uncertainties originate from.

We appreciate the suggestion to use bootstrapping to get an estimate of the uncertainty associated with the "FRE correction factor". We now show the 95% confidence interval of the FRE correction factor in Fig. 3a and we have also made updates to our methods, results and discussion sections accordingly. However, we expect that this may be a relative conservative estimate of the total uncertainty, for example because of the difficulties associated with the comparison of field observations with our long term mean 0.25° estimate and the fact that uncertainty may further be affected by the fire diurnal cycle, regionally. We found the "FRE correction factor" to be 1.56, indicating that MODIS derived FRE per unit area burned should be multiplied by a factor of 1.56 to get fuel consumption of the same magnitude as the corresponding field studies. We expect that the decreasing sensitivity of the MODIS instruments towards the swath edges (e.g., Freeborn et al., 2011) is responsible for most of the underestimation of MODIS-derived FRE. Using bootstrapping (n=10,000, method="bias corrected and accelerated bootstrap") we found that the 95% confidence interval of the bootstrapped distribution of the slopes is 1.30 - 1.80. This corresponds to a 16% increase, or decrease, in absolute fuel consumption estimates.

Minor remarks

p. 21, l. 31-32: I don't understand the connection of this sentence with the previous sentences. Can you please clarify it and improve the text.

We mean to say that compared to GFED we find relatively high fuel consumption in many of the more arid regions. This finding suggests that these regions may play a more important role in the inter annual variability of the land carbon sink than what would be expected based on current state of the art biogeochemical models, like GFED4. We have changed the sentence to read:
"The enhanced fuel consumption in arid and semi-arid drylands found here confirms the important role of arid and semi-arid drylands in the inter-annual variability of the global carbon cycle (Poulter et al., 2014)."

Figure 2 a, b and c: It seems that the two maps fit pretty well. I only noticed the biases after the second reading when I saw the labels of the color legend and the different axis ranges in (b). Can you please make the same color legend ranges for both maps and the same ranges for the axes in (b)?

The goal of this figure is to show the reader that the spatial patterns in fuel consumption derived from SEVIRI and MODIS are rather similar, despite the large absolute differences. We discuss the absolute differences both in the results (P11, L11-12) and in the discussion (P20, L19-22). To avoid further confusion we now specifically mention this difference in the caption of Fig. 2: "Note that on average MODIS-derived FC is about twice as large as SEVIRI-derived FC."

Figure 5 and corresponding analysis: Can you really treat fire return period as the independent variable? I assume fire return period and fuel consumption are highly inter-related. Maybe you can explain this better or you could use a different predictor variable. Additionally, it is strange that the high NPP values are at the bottom of the axis. The plot would be easier if NPP increases from bottom to top.

We have chosen NPP and fire return periods because they are often thought of as the main drivers of fuel loads and are responsible for much of the modelled variation in fuel consumption in GFED4s. In more arid areas combustion completeness is often high and fire return period can most likely be thought of as an independent explanatory variable. In more humid regions with more incomplete combustion an effect of fuel consumption on fire return periods may be expected. For example, when lower fuel loads are associated with higher flammability and thus likelihood of burning. We have now updated the text in the discussion to better acknowledge the possible interaction between fuel consumption, fuel loads and fire return periods.

P23, L19-24 "For example, the highest fuel consumption in the more humid African savannas was found in the most frequently burning grid cells, suggesting a high combustion completeness. In areas where burning is largely limited by fuel humidity, the combustion completeness may have a considerable impact on fuel consumption. The fact that both frequently burning and almost fire free areas occur under similar climatic conditions in (sub)tropical savannas suggest that fuel conditions are important, while frequent fire occurrence may enhance flammability (Shea et al., 1996; Ward et al., 1996)."

In addition, we have also reversed the y-axis of Figure 5.

Table 1: Can you add the references as additional column to improve readability?
- Done

References

Freeborn, P. H., Wooster, M. J. and Roberts, G.: Addressing the spatiotemporal sampling design of MODIS to provide estimates of the fire radiative energy emitted from Africa, Remote Sens. Environ., 115, 475–489, 2011.

Poulter, B., Frank, D., Ciais, P., Myneni, R. B., Andela, N., Bi, J., Broquet, G., Canadell, J. G., Chevallier, F., Liu, Y. Y., Running, S. W., Sitch, S. and van der Werf, G. R.: Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle, Nature, 509, 600–603, 2014.

Shea, R. W., Shea, B. W., Kauffman, J. B., Ward, D. E., Haskins, C. I. and Scholes, M. C.: Fuel biomass and combustion factors associated with fires in savanna ecosystems of South Africa and Zambia, J. Geophys. Res., 101, 23551 – 23568, 1996.

Ward, D. E., Hao, W. M., Susott, R. A., Babbitt, R. E., Shea, R. W., Kauffman, J. B. and Justice, C. O.: Effect of fuel composition on combustion efficiency and emission factors for African savanna ecosystems, J. Geophys. Res., 101, 23569 – 23576, 1996.

Interactive comment on “Biomass burning fuel consumption dynamics in the (sub)tropics assessed from satellite” by N. Andela et al.

General Comments:

This paper describes an approach for combining satellite observations of active fires and burned areas to generate maps of average fuel load consumption (kg m-2) across South America, Africa, and Australia at 0.25 degree grid cell resolution. The ability to develop such a map is at the forefront of wildland fire science, and the production of an accurate map would certainly improve our understanding of global biomass burning and the pyrogenic carbon budget. However, as the authors demonstrate and fully admit, there is uncertainty in their map.

Uncertainties in estimates of fuel load consumption undoubtedly stem from the limitations of confidently measuring fire activity from satellite sensors. To address these satellite sensor limitations, the authors compare fuel load consumption estimates obtained from geostationary and polar orbiting platforms. However, as broached in the specific comments, it is not entirely apparent that their technique for aligning the active fire and burned area products completely restricts comparisons between the geostationary and polar orbiting observations to the same fire activity. Satellite sensor limitations are also addressed by calibrating satellite measurements with field measurements and deriving an alternative, sensor specific conversion factor relating radiant heat release and fuel consumption. However their intent for using an alternative con-version factor – rather than applying a bias correction to satellite-based estimates of FRP and FRE – deserves more consideration.

Aside from the techniques used to produce their map of fuel load consumption, the authors do not fairly acknowledge one aspect – and perhaps the one overarching aspect: the role that environmental conditions and fuel moisture contents play in fuel load consumption. Although NPP and time since fire are used to explore geographical differences in fuel load accumulation, little to no credit is given to the impact that environmental conditions and fuel moisture contents have on consumption completeness. It is very difficult to confidently interpret fuel load consumption estimates between geographical regions without knowing the environmental and fuel moisture conditions at the time of burning.

In my opinion, uncertainties in their fuel load consumption map due to satellite sensor limitations, and the somewhat incomplete interpretation of their map in the absence of fuel moisture contents, does not detract from the overall worthiness of this work. It is a very good start in the right direction, and at the very least, exposes areas for further refinement and opens arenas for further exploration. With some further clarification and explanation, I feel that this article can contribute to our understanding of global biomass burning and pave the way for more accurate fuel load consumption maps in the future.

We would like to start thanking the reviewer for his thoughtful and constructive remarks. Please see our response to the specific comments and technical corrections below. In addition, we will upload a pdf file containing the suggested textual changes in response to both reviews (using track change) and the updated figures, references to line numbers used here refer to this document.

Specific Comments:

1. Page 2, Line 19:

For brevity the authors refer to fuel consumption per unit area burned (kgm-2) simply as fuel consumption. Granted the authors state this up front, but this is the only place that it is mentioned. Anyone skipping the introduction and skimming the methods and results might confuse the traditional sense of fuel consumption (kg) with the authors definition of fuel consumption (kg m-2). Moreover, in the conclusions on Page 22 Lines 22-25, are the authors talking about fuel consumption (kg) or fuel consumption (kgm-2)? The pre-burn mass of fuel per unit area (kgm-2) is typically referred to as the "fuel load". The authors should consider whether or not the term "fuel load consumption" better describes what they are attempting to estimate. In my opinion, the terms "fuel load consumption" and "fuel load consumed" are more accurate descriptors that pose less of a chance for confusion.

To our knowledge "Fuel consumption" is generally defined as:
"A direct measurement of how much biomass was consumed or volatilized in a fire, usually expressed as a mass per unit area (on a dry basis). Biomass loading x combustion factor is one way to estimate fuel consumption. Another way is to average the relevant fuel consumption measurements."
See "A Consistent Set of Biomass Burning Terminology" by Yokelson et al., but also the literature cited in our BGD paper.

In our manuscript all instances of 'fuel consumption' have the same physical meaning and units of kg m^{-2}. However, we appreciate that differences in the interpretation of such concepts may exist. We now repeat our definition of "fuel consumption" at the beginning of the discussion and conclusions sections, in addition the units are mentioned on all the figures and in the table.

2. Page 4, Line 26 – Page 5, Line 2:

Does a description of the "mean fire return period" belong in the Data section, or should it be moved to the Methods section? Also, I understand that the authors are trying to quantify the amount of time between fires as a way of explaining fuel accumulation and eventually fuel load reduction. However I think they may have their terms confused, and I'm not entirely clear on how the "mean fire return period" is calculated. The authors state that: "We estimated the mean fire return period based on the 14 years of MCD64A1 burned area data, by recording how many times each 500 m resolution MODIS grid cell had burned during the 2001 – 2014 period and then dividing this by the 14 years." According to this definition, the "mean fire return period" in a 500 m grid cell can range 0.07 "fires" per year if the grid cell burned once to 1.00 "fire" per year if the grid cell burned every year (with 0's excluded). First things first: metrics with units of inverse time are frequencies. Rather than calculating the "fire return period," it seems to me that the authors are calculating the fire frequency of a 500 m grid cell. The inverse of the fire frequency is the fire return period, which in this case would range from 1 yr if the grid cell burned every year to 14 yrs if the grid cell burned only once during the study period. On Page 12, Lines 23-24, the authors report a "mean fire return period 1.75 years", leading me to believe that they are computing a frequency, but reporting a period. Please confirm?

Also, the authors state that: “We then calculated the mean fire return period for each 0.25° grid cell as the mean return period of all 500 m grid cells within each 0.25° grid cell, weighted by burned area.” Again, from their description, I would expect the “mean fire return period” to be considerably less than 1.00 unless every 500 m pixel within a 0.25° grid cell burned every year, which doesn’t agree with values such as 3 – 8 years reported on Page 15, Lines 13-19. Beyond the period/frequency issue, I do not understand how the “mean fire return period” in a 0.25 degree grid cell is weighted by burned area. Please elaborate. To me, it almost sounds like the authors are trying to calculate a “fire rotation”, or the amount of time it takes to burn an area equal to the size of the study area. All in all, the authors should confirm and clarify their computation of a “mean fire return period” for a 0.25 degree grid cell.

We apologize for our confusing description of how we estimate the fire return period. In contrast to what is stated in the discussion paper (“.. and then dividing this by 14 years.”) we have estimated the fire return period for each 500 m pixel by dividing 14 by the number of times that the pixel burned (units are thus yr and not yr^{-1}). A fire return period of 1.75 years thus correspond to a 500 m pixel that has burned 8 times during the 14 year study period.
*Considering the estimation of the mean fire return period per 0.25° grid cell, what we mean to say by “weighted by burned area” is that a 500 m pixel that burned every year (fire return period of 1 yr) causes 14 times the burned area of a pixel that only burned once during the study period (fire return period of 14 yrs). So the “mean fire return period weighted by burned area” of these two pixels would be (1*14 + 14*1)/15 = 1.86 years. Although this way the mean fire return period will be more heavily influenced by the frequently burning grid cells, the mean fuel consumption estimate is calculated in a similar manner, and we therefore expect that this way the fire return period may better explain the spatial distribution of our fuel consumption estimates.*

We made the following textual changes, to provide a better explanation of how we estimate the fire return period at 0.25° spatial resolution:
Page 4, line 31 – page 5, line 1 “The fire return period is estimated as 14 divided by the number of times that a given grid cell burned during the 14 year study period.”
Page 5, lines 5 – 10 “We then calculated the mean fire return period for each 0.25° grid cell as the mean return period of all 500 m grid cells within each 0.25° grid cell, weighted by burned area. When estimating the mean fire return period per 0.25° grid cell, a 500 m grid cell with a fire return period of 1 year (burning 14 times during the study period) was thus assigned a weight 14 times larger than a 500 m grid cell that burned only once during the study period (having a fire return period of 14 years). We decided to weigh the fire return period by burned area to facilitate the interpretation of the mean fuel consumption conditions, that will in a similar way be dominated by the most frequently burning grid cells.”

3. Page 7, Lines 11-20:
It seems to me that aligning the active fire and burned area products is absolutely crucial to the estimation of fuel load reduction. Although aligning the active fire and burned area pixels is technically feasible, the underlying “squishy” part of this process (which the authors briefly touch upon) is ensuring that the FRP detected by SEVIRI is only emitted from burned areas detected by MODIS, and conversely, that all the burned areas detected by MODIS contribute to some of the FRP measured by SEVIRI. Can the authors perform a sensitivity analysis to quantify the impact of the 15-

day window on their estimates of fuel load consumption? It seems to me that expanding the 15-day window around the burned area detection date would result in more active fire pixels associated with the same burned area and thus result in higher estimates of fuel load consumption. Similarly, contracting the 15-day window would result in lower fuel load consumption estimates. Please confirm, and consider warning the reader about the sensitivity of fuel load consumption estimates to the 15-day window. Also, SEVIRI grid cells with burned area detections but no active fire detections were excluded from the analysis. However the authors never describe how they treat SEVIRI active fire pixels with no corresponding MODIS burned area detections. Were there any?

We agree that the 15 day window is somewhat arbitrary and window size will affect the amount of FRE associated with a certain area burned. The relatively large window (15 days) was chosen because of the possible uncertainty in the burn date (see Fig. 11 in Giglio et al., 2013), and because a fire may burn for several days before the full grid cell is burned. The latter issue may be more important in case of the SEVIRI data, with a spatial resolution of 3x3 km at nadir, than for MODIS with a spatial resolution of 1x1 km. Roberts et al. (2011) *investigated this issue and show the distribution of the active fire detections around the estimated day of burn by the burned area product (see Fig. 1 in Roberts et al., 2011). They find that >80% of SEVIRI active fire detections occur within 2 days before or after the day of burn as determined by the burned area product, after which the sensitivity rapidly decreases. As may be expected the curve was positively skewed, and more than 50% of the active fire detections occur after the burned area detection. The effect of increasing the time window of 15 days as used in our BGD paper would thus be small, the effect of a small decrease in the time window would also be limited but it is crucial to maintain an absolute minimum of 5 days.*

In addition it is possible that two active fires burn at the same time within a given >9 km^2 SEVIRI grid cell. If one of the two fires leaves burned area and the other does not this could in theory cause an overestimation of FRE per unit of area burned and thus of fuel consumption. Given Fig. 1 of Roberts et al. (2011) we argue that this effect is likely small because of: (i) the shape of the curve and the restricted time window, and (ii) the fire that leaves detectable burned area will in general be significantly larger than the fire that does not and will therefore be responsible for most of the FRE. Also, it may occur that burned area is observed by MODIS but no corresponding FRE by the SEVIRI instrument. This was the case for ~3% of annual burned area and this data was excluded because it was impossible to estimate fuel consumption if no FRP was observed. We expect that these instances were mostly related to periods of cloud cover or fires burning at low intensity. The fact that only 3% of annual burned area had no corresponding FRE, while a much larger fraction of the observed FRE (by SEVIRI) had no corresponding burned area suggests that although the sensitivity of the SEVIRI instrument to small fires is much smaller than that of the MODIS instruments, it may still be larger than that of the burned area product. Therefore we assume that instances of two fires burning within the 15 day time window and a given ~9 km^2 SEVIRI grid cell that both leave burned area but of which only one is detected by the SEVIRI instrument are rare. Nonetheless it is clearly possible, especially under conditions of cloud cover. Although it is an interesting and important discussion, we expect that other sensor specific aspects (e.g., related to the pixel size and the ability to detect low FRP fires) are the main source of errors.

In the updated manuscript we discuss the possible effects of the 15-day time window and of excluding burned area without corresponding FRP in more detail:

Page 7, lines 23-33 "Because of the uncertainty of the burn date in the burned area product (Boschetti et al., 2010; Giglio et al., 2013), and the fact that a fire can burn multiple days, we followed Roberts et al. (2011) and assumed that all FRP detections within one week of the burned area observations (before or after; i.e., in total 15 days) in a given grid cell belonged to the same fire. Roberts et al. (2011) investigated the distribution of active fire detections in the days around the "day of burn" as determined by the burned area data set and showed that >80% of the SEVIRI active fire detections occurred within 2 days before or after the day of burn, after which the sensitivity rapidly decreases. Using a 15 day time window thus includes nearly all FRE that can be associated with a given fire, while the possible effect of small fires with observed FRP but without corresponding burned area (burning within the same pixel and time window) on the fuel consumption estimates is likely small. Grid cells having only burned area observations but no corresponding FRP detections are likely related to fires having relatively low FRP or those that were obscured by clouds (Roberts et al., 2011). These areas (3% of annual burned area) were excluded from our analysis."

4. Page 7, Line 23:

Please confirm the value of the conversion factor. There are several instances that reference a value of 0.356 kg MJ-1, and there are several other instances that reference a value of 0.368 kg MJ-1. Which value are you using?

We thank the reviewer for pointing out this error, there is only one correct value derived by Wooster et al. (2005) and that is 0.368 kg MJ-1, which is the value we used in this paper.

5. Page 7, Lines 22-29:

Please see my comments concerning the interpretation of the "mean fuel load consumption" calculated using observations accumulated over long time periods (Page 8, Line 27 – Page 9, Line 2).

Please see response to "specific comment 6" (below).

6. Page 8, Line 27 – Page 9, Line 2:

Yes, I agree with the authors here. However I think they are overlooking a critically important aspect. Accumulating observations over long time periods (e.g., over many years) precludes a seasonal analysis. For the moment, consider a hypothetically static pre-burn fuel load that does not vary from the end of one rainy season to the beginning of the next rainy season. For a constant pre-burn fuel load that does not change over time, fuel load consumption will still vary depending on when during the dry season the landscape burns due to seasonal oscillations in fuel moisture contents, which drive seasonal oscillations in consumption completeness (Hoffa et al., 1999). Accumulating observations over long time frames fails to resolve the seasonal oscillations in consumption completeness and thus fuel load consumption. I strongly suggest that the authors warn the reader that estimates of fuel load consumption calculated from observations accumulated over long time periods are more representative of values observed at the peak in fire activity when the satellites detect the most active fire pixels and burned area pixels within a 0.25 degree grid cell.

Here's the really important bit though: the seasonality of fire activity is not always synchronized with the seasonality of fuel moisture contents and consumption completeness (Le Page et al., 2010). Hence peaks in fire activity may not always coincide with identical fuel moisture conditions. Across the majority of Brazil, for example, the peak in fire activity generally occurs when fuels are driest (i.e., the middle of the fire season coincides with the middle of the CBI season, according to Figure 4 of Le Page et al., 2010). In contrast, across much of Africa, the middle of the fire season occurs before the middle of the CBI season. Therefore, even if the pre-burn fuel loads are identical between South America and Africa, the consumption completeness (%) at the time of peak fire activity would differ between the two locations due to differences in the seasonal synchronization of fire activity and fire weather, which would then lead to different estimates of fuel load consumption.

The authors do a nice job of using NPP and time since fire to explain geographical differences in the pre-burn fuel load, however they do not account for differences in consumption completeness (%), a value just as important in traditional estimates of fuel load consumption. In my opinion, the inability to identify fuel moisture conditions at the time of burning hinders a complete and confident interpretation of the geographical differences in fuel load consumption. Aligning the active fire and burned area pixels with a map of fuel moistures at the time of burning would be the ideal solution. However if the authors forgo such an analysis, they should at least make it extremely clear to the reader that fuel load consumption depends on the pre-burn fuel load AND consumption completeness, and that the latter is influenced by the environmental conditions and fuel moisture contents at the time of burning, which are not accounted for here.

We agree that in addition to fuel loads fuel moisture plays an important role in the eventual fuel consumption by affecting the combustion completeness, and this likely explains part of the observed spatial variability in our long term mean fuel consumption estimate. However, in this manuscript much of our attention was focused on our main objective: "to derive mean fuel consumption estimates". We indeed carry out a first exploration of the possible drivers of the observed spatial patterns but limit ourselves to directly analyse the effect of NPP and fire return periods, partly because these can be relatively well observed from space and partly because they are expected to be key drivers of fuel consumption. Therefore it is only in the discussion that we mention the role of fuel humidity and combustion completeness on fuel consumption. A more detailed analysis, also including the temporal variation, would form an interesting follow up study. We have now expanded our discussion, to better highlight the importance of fuel moisture and combustion completeness and to discuss where largest effects may be expected and why (see updated sect. 5.2).

Page 22, lines 10 – 14 "Fuel consumption depends on the amount of fuel available for burning and the combustion completeness. In arid areas available fuel and thus fuel consumption is often limited by precipitation. Across these arid and semi-arid areas precipitation generally determines vegetation productivity and tree cover. Grasses in these more arid ecosystems often have a combustion completeness above 80% (van Leeuwen et al., 2014), and fuel consumption and fuel loads will generally be similar."
Page 23, lines 19 – 30 "For example, the highest fuel consumption in the more humid African savannas was found in the most frequently burning grid cells, suggesting a high combustion completeness. In areas where burning is largely limited by fuel humidity, the combustion completeness may have a considerable impact on fuel consumption. The fact that both frequently burning and almost fire free areas occur under similar climatic conditions in (sub)tropical savannas suggest that fuel conditions are important, while frequent fire occurrence may enhance flammability (Shea et al., 1996; Ward et al., 1996). Short fire return periods provide a competitive advantage to

herbaceous vegetation over woody vegetation (Bond et al., 2005; Bond, 2008). A high degree of canopy openness will result in more grass covered area and higher dry season ground surface temperatures and lower fuel moisture content resulting in high combustion completeness. However, a similar temperature or moisture driven effect may also be caused by the timing of the ignitions (Hoffa et al., 1999) directly related to management practices. Le Page et al. (2010) showed that African savannas typically burn early in the dry seasons, while Australian savannas often burn later in the season."

7. Page 10, Line 9 – Page 11, Line 14:

Since the MCD64A1 product is used for both estimates, can it be assumed that the differences between FC MODIS and FC SEVIRI are entirely attributed to the different active fire products and the different methods for converting FRP to FRE?

In the BGD paper it could in addition be explained by inter annual variation in fuel loads and combustion completeness since we compared MODIS derived fuel consumption (2003-2014) with SEVIRI derived fuel consumption (2010 – 2014). We have now updated Fig. 2 and compare MODIS and SEVIRI based fuel consumption over the same 2010 – 2014 time period. Therefore it can now be assumed that most differences indeed stem from sensor specific issues and different methods related to that, like the fire diurnal cycle in combination with the MODIS sampling design. Interestingly, little changes occurred in figure 2, indicating that although there may be diurnal, seasonal and inter annual variation in fuel consumption, the sample of 2010 – 2014 is reasonably similar to the longer term mean over 2003 – 2014. Note that to estimate r^2 (Fig. 2b) we exclude infrequently burning areas with burned area below 15% yr^{-1}, which may partly explain the good comparison using the different time periods.

8. Page 10, Line 9 – Page 11, Line 14:

I'm curious about how much overlap there is in the fire activity that's driving the two estimates of fuel load consumption. I mean, are FC MODIS and FC SEVIRI driven by the same fire activity, or are they two different sets of fire activity, or is the fire activity that that drives FC SEVIRI a subset of the fire activity that drives FC MODIS? Based on the author's statement on Page 8, Line 21: "In contrast to the approach based on SEVIRI data, here all burned area observations were included", it would seem to me that FC SEVIRI is driven by fire activity that is a subset of the fire activity that is driving FC MODIS, if FC MODIS is limited to 2010-2014. Can any insights be gained by limiting the calculation of FC MODIS to the time period used to calculate FC SEVIRI (2010 – 2014)? Perhaps not the bias, but it seems to me that the scatter in the relationship between FC MODIS and FC SEVIRI could be due to the possibility that MODIS and SEVIRI are observing different fire activity within the same 0.25 grid cell. I may be mistaken, but I don't think this was ever offered as an explanation for the scatter. Unless the authors can demonstrate that estimates of FC MODIS and FC SEVIRI are driven by the same fire activity, then I think they have to concede that the scatter in the relationship could be attributed to the possibility that MODIS and SEVIRI are observing different fires within the same grid cell. Note that if fuel load consumption is homogeneous within a 0.25 degree grid cell, then it doesn't matter what fire activity MODIS and SEVIRI observed. However by their own admission, fuel load consumption is heterogeneous, and therefore has the potential to induce scatter in the relationship between FC MODIS and FC SEVIRI if MODIS and SEVIRI observe different fires within the same grid cell.

In general it can be assumed that the MODIS instruments observe many "small" fires, that fall below the detection threshold of the SEVIRI instrument. However, the burned area product does not detect these small fires either, and "small" fires without detected burned area were excluded from the analysis in both the MODIS-derived and SEVIRI-derived fuel consumption estimates (Fig. 1). Moreover, we found that only 3% of annual burned area did not have corresponding SEVIRI FRP detections (Page 7 Lines 32-33). The sensitivity of the SEVIRI product to small fires is thus still be larger than that of the burned area product. Finally, especially in the case of the coarse SEVIRI grid cells (3x3 km at nadir) there is a small chance of small fires (not having burned area) burning alongside the larger fire within the same time window and grid cell. We expect that this effect on our fuel consumption estimates is small, as discussed in our response to "specific comment 3". Both datasets are thus largely based on the same fires (i.e., all the somewhat larger fires with burned area, except for the 3% excluded in the SEVIRI-approach). However, neither of the products (MODIS or SEVIRI) can observe the fire during its full life cycle, likely leading to most of the observed differences, as discussed below.

We have now made the comparison of SEVIRI and MODIS fuel consumption estimates based on the same time period (Fig. 2; 2010 – 2014). No major changes occurred in the figure and r^2 remains 0.42, indicating that most differences come from the actual sensor characteristics and related methods. We expect that most differences between the MODIS- and SEVIRI-derived fuel consumption estimates are caused by the different sensitivities of the MODIS and SEVIRI instruments and the fire diurnal cycle. Although the MODIS and SEVIRI instruments observe the same fires, as discussed above, they will observe those fires at different moments in time. The MODIS instruments only make observations at the fixed hours of their overpasses, while the SEVIRI instrument only observes the fire while FRP is above its much higher detection threshold. While peak daily fire activity of a fire large enough to leave a detectable burned area is nearly always observed by the SEVIRI instrument a certain fraction of daily fire activity will fall below its detection threshold. The relative fraction of FRE emitted below the detection threshold is likely a function of: (i) the SEVIRI pixel size, (ii) the shape of the fire diurnal cycle, and (iii) the size of the fire front and fuel consumption rate of the fire, that together drive absolute FRP values and thus SEVIRI's ability to detect the fire. In Fig. 2 two of these aspects clearly stand out:

1. *The increasing SEVIRI pixel size and detection threshold away from the sub satellite point (0° N/S, 0° W/E) clearly lead to an underestimation of fuel consumption over southeast Africa.*
2. *In some areas with high fuel consumption SEVIRI and MODIS-derived fuel consumption estimates are nearly equal (i.e., red color in Fig. 2d), showing that nearly all fire activity occurred above the SEVIRI detection threshold. In areas with many small fires however, often only a relatively small fraction of the daily burning can be observed by the SEVIRI instrument and the MODIS estimates are thus considerably higher than the SEVIRI ones.*

However, in order to fully resolve such issues a combined understanding of the influence of the fire diurnal cycle on both SEVIRI and MODIS FRE estimates is required. We made a start in Andela et al. (2015) *to study the specific impact of the fire diurnal cycle on FRE estimates from MOSIS and to better characterize the fire diurnal cycle over Africa. But this is still an ongoing field of research.*

In addition to the adjustments to Fig. 2, we have made several textual changes to reflect our current understanding of the differences between MODIS and SEVIRI-derived fuel consumption estimates:

Page 11 lines 12 - 22 "On top of these absolute differences, the spatial patterns were not uniform (Fig. 2b and d), for which we identified two main causes: first the MODIS based fuel consumption was consistently higher in south-eastern Africa (e.g., Mozambique and Madagascar), likely because of the decreasing sensitivity of the SEVIRI instrument at the greater off-nadir angle over this region (e.g., Freeborn et al., 2014)*; and second the relative fraction of FRE emitted during periods that FRP values were below the SEVIRI detection threshold is a function of the absolute FRP values and the shape of the fire diurnal cycle. Fires with high FRP (related to high fire spread rates and/or fuel consumption) are often equally well observed by both instruments (i.e., red color in Fig. 2d), while areas with low fuel consumption are often characterized by a larger differences between the MODIS and SEVIRI estimates (i.e., green color in Fig. 2d)."*

Page 20 lines 13 – 17 "We found that a large part of the differences could be attributed to the different sensors characteristics and methods used here. The shape of the fire diurnal cycle for example affects both MODIS based fuel consumption estimates due to the limited number of daily overpasses but also the SEVIRI derived fuel consumption estimates because it directly affects the relative fraction of daily fire activity that falls below the SEVIRI detection threshold."

Page 20 lines 24 – 29 "In our analysis a small part of the structural difference could also be explained by the fact that we did not correct for cloud cover and/or missing data in the SEVIRI based FC estimates. Not surprisingly, the best comparison between both methods was found in areas of high fuel consumption rates (Fig. 2d), for example areas where fires can spread over large areas to form large fire fronts (Archibald et al., 2013), and areas of high fuel consumption, these fires with high FRP are likely to be well observed by both instruments."

Page 21 lines 1 – 3 "Following previous studies, we find that about half of this discrepancy can be attributed to SEVIRI failing to detect the more weakly burning fires that ultimately are responsible for around half of the emitted FRE (Freeborn et al., 2009, 2014)*."*

9. Page 12, Lines 7 – 14:

I think this section raises a very interesting question: is it reasonable to derive alternative conversion factors (kg MJ^{-1}) for different satellite sensors? To be honest, I don't know the answer to this question, so I leave it to the authors to pontificate. Note that the authors specifically state that: "Although the FRE per unit area burned can be converted to fuel consumption using the conversion factor found by Wooster et al. (2005) during laboratory experiments which we have used so far, some instrument specific issues may further affect the FRE estimates from space (see methods). In order to correct for uncertainties in the MODIS derived FRE estimates, we derived an alternative conversion factor by comparing the MODIS FRE per unit area burned directly to field measurements instead (Fig. 3a)." Here the authors admit that the reason for deriving an alternative conversion factor is because of the biases and uncertainties of estimating FRE from MODIS. If this is the case, then shouldn't the adjustment be more appropriately applied to the detection and conversion of FRP to FRE? Why should it be necessary to adjust an empirically derived "physical constant" due to satellite and sensor limitations? Are the authors suggesting that satellite sensor artefacts be incorporated into combustion chemistry and the relationship between radiant heat release and fuel consumption? Note that 0.356 kg MJ-1 (or 0.368 kgMJ-1) is a laboratory derived value, and as such its inverse represents (as close as possible) the amount of radiant heat released per kg of fuel consumed. Adjusting this value to 0.572 kg MJ-1 means that its inverse has a different interpretation: the amount of radiant heat measured by MODIS per kg of fuel consumed. The difference in the meaning is subtle, but not trivial. For instance, there's a difference between (a) the radiant fraction, and (b) the fraction of total heat released that is measured as radiation by MODIS. The other option is to use the laboratory relationship between radiant heat and fuel consumption (which has a universal, physical meaning), and separately derive a MODIS specific FRP-FRE-adjustment factor to account for sensor limitations. I'll leave it to the authors to explain why deriving alternative, sensor specific conversion factors– as performed here – is a better option than using field measurements to derive an adjustment factor that's applied during the conversion of FRP to FRE. Although the two calibration options will obviously give you the same results, they nevertheless have different meanings.

Our current understanding is that errors in the FRE estimation are indeed likely responsible for most of the difference between the two conversion factors. Considerable errors in absolute FRE estimates may for example be expected due to the MODIS sampling design in combination with the fire diurnal cycle (e.g., Vermote et al., 2009; Andela et al., 2015) *and the increasing pixel size at higher scan angles* (e.g., Freeborn et al., 2011)*. We appreciate the reviewers suggestion and have changed the manuscript accordingly. Rather than deriving an alternative conversion factor we now speak of a "FRE correction factor". In addition we followed the suggestion of reviewer #1 to use bootstrapping to get an estimate of the uncertainty involved with this correction factor (see manuscript with suggested changes and response to reviewer #1).*

10. Page 15, Lines 8 – 20:

To follow on from my previous comment, the authors recognize the role of productivity and fire return periods on the accumulation of fuels, and thus account for the impact of the pre-burn fuel load on fuel load consumption. However, the authors do not equally acknowledge the role of environmental and fuel moisture conditions at the time of burning and their influence on consumption completeness. Ideally the analysis should account for fuel moisture contents at the time of burning. If such an analysis is not feasible, then the authors should make every effort to remind the reader of the impact of different fuel moisture conditions on consumption completeness and thus fuel load reduction.

We agree that fuel moisture (affecting the combustion completeness) is a major driver of spatiotemporal dynamics of fuel consumption, especially in the more humid tropics. We have made several textual adjustments to provide a more complete discussion of the role of fuel moisture and combustion completeness on fuel consumption. Please see our response to "specific comment 6" for further details.

11. Page 18, Lines 15-17:

Couldn't the "large natural temporal variation in fuel consumption combined with the different periods of data availability" be discounted if FC MODIS and FC SEVIRI are compared between 2010-2014? Also, in addition to the different sensor characteristics, aren't there differences in the methods for converting MODIS and SEVIRI measurements of FRP to FRE (i.e., dividing by detection opportunities vs. temporal integration)?

We appreciate this suggestion and now make the comparison (Fig. 2) using the same period (2010 – 2014) for both MODIS and SEVIRI derived fuel consumption. Interestingly, the difference between using MODIS-derived fuel consumption over the period 2010 – 2014 or MODIS-derived fuel consumption over the full study period (2003 – 2014) was small. Despite the temporal variation in fuel consumption the mean over 4 years seems representative for the full study period. For more details, please also see our response to "specific comments 7 and 8".

We agree that differences are both caused by the different sensor characteristics and the different methods to derive FRE per unit area burned from FRP and burned area observations. We have often referred to this as "differences in sensor characteristics", since it is for example the MODIS sampling design (a sensor characteristic) that forces us to choose an alternative way of deriving FRE as opposed to the continuous SEVIRI observations. However, since there are clearly alternative methods to estimate FRE using the MODIS observations it is indeed more correct to speak of "sensor characteristics and methods". We have updated the text accordingly.

12. Page 19, Line 30 – 34:
This is one of only a few places where the authors disclose to the reader that fuel load consumption depends on the pre-burn fuel load and consumption completeness.

Please see our response to "specific comment 6".

13. Page 20, Line 9 – 15:
Indeed. Due to different management goals, fires are lit earlier in the dry season in Africa compared to South America, and particularly in Brazil where fires are generally lit at the peak of the dry season (as shown in Figure 4 of Le page et al., 2010). Hence fire management practices not only determine the fire return period, which affects the fuel load accumulation, but fire management practices also determine what time of year the fires are lit, and thus under what fuel moisture conditions the fires burn. Whilst the authors conclude that fuel load consumption across Africa is relatively low compared to Australia or South America due to differences in the fire return periods, one could also argue that based on the maps presented by Le Page et al. (2010), fuel load consumption is also lower in Africa since fires are more often lit earlier in the dry season when fuel moistures are higher and consumption completeness is lower.

We now referred to the article by Le Page et al. (2010) and we have made several textual adjustments as highlighted in our response to "specific comment 6". Although the timing of the fires undoubtedly affects regional patterns of fuel consumption, especially in the more humid savannas, these patterns are also dependent on many other factors, like fuel loads and dry season duration. Our paper focused preliminary on the possibility of deriving fuel consumption estimates from satellite data while we provide a first exploration of the possible drivers of the spatial patterns. We hope that the new insights of this paper will provide the community with the tools to continue this research, getting to the actual underlying processes in more detail during follow up studies.

Technical Corrections:

1. Page 1, Line 23-24: Incomplete sentence or incomplete thought.

Now changed to "We used field measurements of fuel consumption to constrain our results, but the large variation of fuel consumption in both space and time complicated this comparison and absolute fuel consumption estimates remained more uncertain."

2. Page 2, Line 19-21: Consider changing the sentence to read: "… is a key indicator of the consequences of changing management practices, vegetation characteristics and climate on fire regimes, as well as a key parameter required in fire emissions estimates."
- Done

3. Page 2, Line 21-23: Consider changing the sentence to read: "Yet, spatiotemporal dynamics of fuel consumption on a continental scale remain largely unmeasured and poorly understood (van Leeuwen et al., 2014)."
- Done

4. Page 3, Line 23: Consider changing the sentence to read: "… creating the first fully satellite-derived fuel consumption map for Africa."
- Done

5. Page 4, Line 1-2: Consider changing the sentence to read: "… in an attempt to provide more statistically representative fuel consumption estimates, particularly in less frequently burned grid cells.
- Done

6. Page 4, Line 7-8: Consider changing the sentence to read: "Finally, we used our fuel load reduction map to explore the drivers of fuel consumption in the study regions."
- Not done, see our response to "specific comment 1".

7. Page 4, Line 19-24: It may be helpful to remind the reader here that the MCD64A1 burned area product is also used by GFED.
We now note this when we describe the GFED4s dataset:
Page 6 lines 23 - 25 "Methods used in GFED4s are based on GFED3.1 (van der Werf et al., 2010) but with two main improvements. The first one is the inclusion of small fire burned area in addition to the burned area observed by the MCD64A1 product (Randerson et al., 2012), the second .."

8. Page 6, Line 24: Consider changing the sentence to read: "… first derived a fuel consumption map for Sub-Saharan Africa."
- Done

9. Page 8, Line 33: Grammar, pluralize: "Minimising the impact of these types of perturbations… "
- Done

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Biomass burning fuel consumption dynamics in the ~~(sub)~~tropics and subtropics assessed from satellite

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Abstract. Landscape fires occur on a large scale in (sub)tropical savannas and grasslands, affecting ecosystem dynamics, regional air quality and concentrations of atmospheric trace gasses. Fuel consumption per unit of area burned is an important but poorly constrained parameter in fire emission modelling. We combined satellite-derived burned area with fire radiative power (FRP) data to derive fuel consumption estimates for land cover types with low tree cover in South America, Sub-Saharan Africa, and Australia. We developed a new approach to estimate fuel consumption, based on FRP data from the polar orbiting MODerate-resolution Imaging Spectroradiometer (MODIS) and the geostationary Spinning Enhanced Visible and Infrared Imager (SEVIRI) in combination with MODIS burned area estimates. The fuel consumption estimates based on the geostationary and polar orbiting instruments showed good agreement in terms of spatial patterns~~, but~~. We used field measurements of fuel consumption to constrain our results, but the large variation of fuel consumption in both space and time complicated this comparison and absolute fuel consumption estimates remained more uncertain. ~~Fuel consumption varies considerably in space and time, complicating the comparison of various approaches and using field measurements to constrain our results.~~ Spatial patterns in fuel consumption could be partly explained by vegetation productivity and fire return periods. In South America, most fires occurred in savannas with relatively long fire return periods, resulting in comparatively high fuel consumption as opposed to the more frequently burning savannas in Sub-Saharan Africa. Strikingly, we found the infrequently burning interior of Australia having higher fuel consumption than the more productive but frequently burning savannas in northern Australia. Vegetation type also played an important role in explaining the distribution of fuel consumption, both by affecting fuel build up rates and fire return periods. Hummock grasslands, which were responsible for a large share of Australian biomass burning, showed larger fuel build up rates than equally productive grasslands in Africa, although this effect might have been partially driven by the presence of grazers in Africa~~.~~ or differences in landscape management. Finally, land management in the form of deforestation and agriculture also considerably affected

fuel consumption regionally. We conclude that combining FRP and burned area estimates, calibrated against field measurements, is a promising approach in deriving quantitative estimates of fuel consumption. Satellite derived fuel consumption estimates may both challenge our current understanding of spatiotemporal fuel consumption dynamics and serve as reference datasets to improve biogeochemical modelling approaches. Future field studies especially designed to validate satellite-based products, or airborne remote sensing, may further improve confidence in the absolute fuel consumption estimates which are quickly becoming the weakest link in fire emissions estimates.

1 Introduction

Landscape fires play an important role in many ecosystems across the globe, with (sub)tropical savannas of intermediate productivity being most frequently burned (Bowman et al., 2009). Within those (sub)tropical ecosystems, humans are responsible for most of the ignitions and fires have been actively managed for thousands of years (Stott, 2000; Archibald et al., 2010, 2012), partly aided by the vegetation traits of these regions which make them inherently flammable (Archibald et al., 2009). Landscape fires promote open canopy grassy vegetation over closed canopy woody vegetation (Scholes and Archer, 1997; Bond et al., 2005; Lehmann et al., 2011), providing competitive advantages to grassy rather than woody species in frequently burning landscapes (Sankaran et al., 2008). This fire driven tree – grass competition is further affected by the occurrence of different vegetation traits on the continents (Staver et al., 2011; Lehmann et al., 2014; Moncrieff et al., 2014). Due to the large scale at which biomass burning occurs, inter-annual variability in landscape fires is directly related to (greenhouse) gas concentrations in the atmosphere (Langenfelds et al., 2002) and affects regional air quality (Crutzen et al., 1979; Langmann et al., 2009; Turquety et al., 2009; Aouizerats et al., 2015). Fire regimes and fire management vary widely across (sub)tropical regions (Archibald et al., 2013), while ongoing socio-economic developments are expected to increasingly affect landscape fires and vegetation patterns during the coming century (Chen et al., 2013; Grégoire et al., 2013; Andela and van der Werf, 2014). Fuel consumption per unit area burned (kg m^{-2}), hereafter called fuel consumption for brevity, is a key ~~parameter to better understand~~indicator of the consequences of changing management practices, vegetation characteristics and climate on fire regimes, ~~or to estimate~~as well as a key parameter required in fire emissions estimates. Yet, spatiotemporal dynamics of fuel consumption on a continental scale remain largely unmeasured and poorly understood (van Leeuwen et al., 2014).

With global annual burned area exceeding the size of India (Giglio et al., 2013) or even the European Union (Randerson et al., 2012), satellite remote sensing is an important source of data to understand the spatiotemporal dynamics of fire. Over the last decade, several new satellite observing systems have become operational, greatly improving our understanding of fire dynamics and fire emission estimates. For example, vegetation productivity (Running et al., 2004) and fire return periods (Archibald et al., 2013) can now be estimated using satellite imagery and data. Broadly speaking, two types of satellite datasets are available to study fire dynamics. These are satellite-derived estimates of burned area that are based on changes in surface reflectance over time (Giglio et al., 2006b, 2013) and active fire observations often accompanied by information on fire radiative power (FRP; Giglio et al., 2006a; Roberts and Wooster, 2008).

Both data types have advantages and disadvantages for the purpose of estimating fire emissions. Burned area remains visible for several days to months after the fire occurred, allowing observations of fires that were obscured by clouds during the satellite overpass, as long as cloud cover is not too persistent (Roy et al., 2008). However, small fires are generally not detected by the burned area algorithm (Randerson et al., 2012) and fuel consumption has to be modelled in case burned area is used to calculate emissions (van der Werf et al., 2010). Active fire observations on the other hand often include FRP associated with the detected fire, which can be used to estimate fire radiative energy (FRE) which is directly related to dry matter burned (Wooster et al., 2005). When FRP data of geostationary instruments are used, the full fire diurnal cycle is observed and FRE and dry matter burned can be estimated by integrating the FRP observations over time (Roberts et al., 2005). However, geostationary satellites are located relatively far from the Earth and therefore have a relatively coarse pixel size. Consequently ~~the smallest~~ fires with low FRP ~~often~~ fall below their detection threshold (Freeborn et al., 2009). Polar orbiting ~~satellites~~instruments, like the MODerate-resolution Imaging Spectroradiometer (MODIS) are located closer to the Earth and therefore have a higher spatial resolution and sensitivity to ~~small~~ fires with low FRP. However, with approximately four daily observations under ideal conditions the MODIS instruments provide relatively poor sampling of the fire diurnal cycle (Ellicott et al., 2009; Vermote et al., 2009; Freeborn et al., 2011). On top of the orbit-specific limitations, active fire observations from both polar orbiting and geostationary instruments are sensitive to cloud cover, and radiation of surface fires may be partly obscured by tree cover (Freeborn et al., 2014a).

To date, most knowledge on fuel consumption dynamics stems from a limited number of field campaigns (summarized in van Leeuwen et al., 2014). These studies provide great detail and have considerably advanced our understanding of fuel consumption dynamics, but upscaling is problematic because fuel consumption is highly variable in space and time (Hoffa et al., 1999; Hély et al., 2003b; Boschetti and Roy, 2009). As an alternative approach, Roberts et al. (2011) combined burned area data from MODIS with FRE estimated from the geostationary Meteosat Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument, creating the first fully satellite-derived fuel consumption ~~estimate~~map for Africa. Although at that time only one year of SEVIRI data was available, Roberts et al. (2011) found some striking differences between their estimates of fuel consumption and the ones resulting from the biogeochemical modelling framework used in the Global Fire Emission Database version 3 (GFED3; van der Werf et al., 2010). The satellite-derived fuel consumption estimates of Roberts et al. (2011) were considerably lower than the ones from GFED in savanna regions, which may partly be explained by the low sensitivity of the SEVIRI instrument to small fires and an overestimate by GFED3. However, spatial patterns were also different, indicating that such methods can provide new insights in the distribution of fuel consumption and of fuel build up processes.

The objective of this study is to gain further insights into the spatial distribution and drivers of fuel consumption. Initially, fuel consumption is estimated across Sub-Saharan Africa, by building upon the previous work of Roberts et al. (2009, 2011) that combined active fire FRP data from the geostationary SEVIRI instrument with burned area data from MODIS. We used a similar approach, but with longer time series (2010 – 2014) in an attempt to provide more statistically representative fuel consumption estimates, for exampleparticularly in less frequently burning grid cells. Then we used a similar method but now based on MODIS FRP data to expand our study region to include South America and Australia, in addition to Sub-Saharan Africa. In situ fuel consumption observations were used to calibrate the MODIS-derived fuel consumption estimates to match field-measured values. Because FRP observations may be partly obscured by tree cover (Freeborn et al., 2014a), we limited our study to low tree cover land cover classes. Results were compared to the SEVIRI-derived fuel consumption estimates, and that derived using the biochemical GFED modelling framework. Finally, we used the spatial distribution of our fuel consumption estimates to explore the drivers of fuel consumption in the study regions.

2 Data

In this study we combined burned area data (Sect. 2.1) with FRP data to derive fuel consumption estimates. We commenced by following the approach of Roberts et al. (2011), based on FRP data provided by the geostationary SEVIRI instrument (Sect. 2.2), and then developed a new method using the FRP data from the polar orbiting MODIS instruments (Sect. 2.3). Information on land cover type, fire return periods and net primary productivity (NPP) were used to better understand the spatial variation in fuel consumption while results were also compared to fuel consumption estimates extracted from the GFED4s dataset (Sect. 2.4). Both methods to derive fuel consumption were based on the native resolution of the FRP data, but end results were rescaled to 0.25° resolution, for comparison to drivers and in case of the MODIS FRP-detections to include a representative sample size.

2.1 MODIS burned area

The MCD64A1 burned area dataset, based on land surface spectral reflectance observations made by the MODIS instruments aboard the Terra and Aqua satellites, provides daily 500 m resolution global burned area estimates from August 2000 onwards (Giglio et al., 2009, 2013). Partly because of the relatively high spatial resolution of the MODIS instruments, MODIS based burned area data was found to perform best out of several burned area products (Roy and Boschetti, 2009; Padilla et al., 2014). Despite this relatively good performance, the burned area product still often misses the smallest fires, which according to Randerson et al. -(2012) may comprise a large fraction (over one third) of the overall global burned area.

We estimated the mean fire return period based on the 14 years of MCD64A1 burned area data, by recording how many times each 500 m resolution MODIS grid cell had burned during the 2001 – 2014 period and then dividing this by the 14 years.. The fire return period is estimated as 14 divided by the number of times that a given grid cell burned during the 14 year study period. This method yields best results for frequently burning grid cells where the accuracy is thought to be high. For grid cells burning only once during the 14 years it is likely that in many cases the actual fire return period may in fact be longer, leading to an ~~overestimation~~underestimation of fire return periods. For grid cells without any burned area observations no fire return period could be calculated. We then calculated the mean fire return period for each 0.25° grid cell as the mean return period of all 500 m grid cells within each 0.25° grid cell, weighted by burned area. When estimating the mean fire return period per 0.25° grid cell, a 500 m grid cell with a fire return period of 1 year (burning 14 times during the study period) was thus assigned a weight 14 times larger than a 500 m grid cell that burned only once during the study period (having a fire return period of 14 years). We decided to weigh the fire return period by burned area to facilitate the interpretation of the mean fuel consumption conditions, that will in a similar way be dominated by the most frequently burning grid cells.

2.2 SEVIRI FRP data

The SEVIRI instrument, aboard the geostationary Meteosat Second Generation satellites is located at 0° longitude and latitude and provides active fire observations at 3 km spatial resolution at nadir, degrading with increasing view angle (Roberts and Wooster, 2008; Freeborn et al., 2011). The sensitivity of the instrument to ~~small~~ fires with low FRP is lower than the sensitivity of the MODIS instruments due to the coarser pixel size, but the instrument provides 15 min interval observations capturing almost the full fire diurnal cycle, cloud cover permitting. Here we used the Meteosat SEVIRI FRP-PIXEL product providing FRP data at 15 min interval on the original SEVIRI spatial resolution (Roberts and Wooster, 2008; Wooster et al., 2015). The FRP-PIXEL product is freely available and can be downloaded from the Land Surface Analysis Satellite Applications Facility (http://landsaf.meteo.pt), from the EUMETSAT EO Portal (https://eoportal.eumetsat.int/) or via the EUMETCAST dissemination service (http://www.eumetsat.int), both in real-time and archived form.

2.3 MODIS FRP data

The MODIS instruments aboard the polar orbiting Terra (MOD) and Aqua (MYD) satellites provide global FRP data at 1 km resolution (Giglio et al., 2006a). To calculate fuel consumption we used the MOD14 and MYD14 version 005 active fire data for the full period that both satellites were in orbit (2003 – 2014). The 1 km resolution translates into a higher sensitivity to small fires (i.e., low FRP), although the FRP sensitivity of MODIS decreases towards the swath edges (Freeborn et al., 2011). Because of the importance of a large sample size for our analysis, we included the MODIS FRP data from all active fire detections (low to high confidence active fire pixels).

The number of daily overpasses of the MODIS instruments is lowest in the tropics and increases towards the poles due to orbital convergence. Cloud cover permitting, the two MODIS instruments provide around four daily observations in the (sub)tropics. We combined information from the MOD03 and MYD03 geolocation datasets associated with each MODIS overpass with the MOD14 and MYD14 cloud cover data, to derive the mean daily MODIS detection opportunity (i.e., cloud free overpasses) during the burning season in a similar way to the processing used in the Global Fire Assimilation System (GFAS; Kaiser et al., 2012). Because of the large size of the MOD03 and MYD03 data we based this part of the analysis on 4 years of data (2009 – 2012), enough to calculate a representative mean value. MODIS data are freely available and can be downloaded from NASA at http://reverb.echo.nasa.gov.

2.4 Other datasets

We derived information on land cover type from the MODIS MCD12C1 version 051 product, using the University of Maryland land cover classification (Friedl et al., 2002). In this study we focussed on low tree cover vegetation types including savannas, woody savannas, grasslands, shrublands and croplands. Forests and bare or sparsely vegetated areas were excluded. Because the land cover fraction having closed shrublands was small and contained very little of the overall fire activity, we merged open and closed shrublands into one 'shrubland' class. The dominant land cover type was based on 2003 – 2012 data, because post 2012 data was not available to us at the time of the study.

Net Primary Production (NPP) was derived from the Terra MODIS MOD17A3 version 055 1 km annual product (Running et al., 2004), and we used the mean NPP over 2003 – 2010 (post 2010 data was not available). Units of NPP were in g C m^{-2} yr^{-1}, and for comparison to estimates of fuel consumption in units of dry matter (DM) burned per m^2 we assumed a vegetation (fuel) carbon content of 45% (Andreae and Merlet, 2001; Barbosa and Fearnside, 2005).

Fuel consumption estimates from field studies were used to calibrate and evaluate the fuel consumption estimates from satellite. Peer reviewed studies were compiled into a field observation database for several biomes by van Leeuwen et al. (2014), and here we used their values for the savanna biome, including grasslands and (woody) savannas.

Finally, we compared our results to modelled fuel consumption estimates over the same period (2003 – 2014) extracted from the GFED4s dataset (0.25° spatial resolution). Methods used in GFED4s are based on GFED3.1 (van der Werf et al., 2010) but with two main improvements. The first one is the inclusion of small fire burned area in addition to the burned area observed by the MCD64A1 product (Randerson et al., 2012), the second one is further tuning of the model to better match fuel consumption estimates from the database of van Leeuwen et al. (2014). This involved mostly faster turnover rates of leaf and litter in the model to lower fuel consumption rates in low treecover regions. GFED data can be downloaded from http://globalfiredata.org/.

3 Methods

The primary objective of this study was to provide further insights into the spatial distribution of vegetation fire fuel consumption in key (sub)tropical biomass burning regions, and also to provide insights into its most important drivers. We first derived a fuel consumption ~~estimate~~map for Sub-Saharan Africa using SEVIRI FRP data and the MCD64A1 burned area product, using an approach similar to that of Roberts et al. (2011). We derived FRE ~~from~~per unit area burned by combining the SEVIRI FRP data and burned area data, which was subsequently converted to an estimate of fuel consumption (in kg DM-burned per m^{-2} burned) using the conversion factor of Wooster et al. (2005), see Sect. 3.1. To expand our understanding of fuel consumption beyond Africa, we explored if a similar approach could be applied to MODIS FRP data. This approach was similar to the methods of Kaiser et al. (2012) but with a few adjustments to calculate fuel consumption. ~~Rather than using a conversion factor based on laboratory experiments as in Wooster et al. (2005), we related the FRE to~~Because of the uncertainties in the absolute FRE estimates, we correct the FRE estimates by calibration against in situ field observations to estimate fuel consumption (Sect. 3.2). We present results of this processing for three (sub)tropical biomass burning regions: South America, Sub-Saharan Africa and Australia. In those regions we explored the potential drivers of the spatial distribution of fuel consumption. Fuel consumption also varies in time, as a function of fuel loads and combustion completeness. These temporal effects are not specifically investigated here, but are discussed in the discussion. Finally, the results were compared to model-derived fuel consumption estimates of GFED4s.

3.1 Converting SEVIRI FRP to fuel consumption using laboratory measurements

Roberts et al. (2011) combined estimates of dry matter burned (kg), based on one year of FRP data from the geostationary Meteosat SEVIRI instrument, with MODIS-derived burned area mapping (m^2) to derive fuel consumption estimates (kg m^{-2}) for Africa. Here we followed a similar approach, but now we included five years of SEVIRI data (2010 – 2014), to get a better understanding of fuel consumption in infrequently burning zones, and to derive more representative mean fuel consumption estimates in general. An overview of this method is given in the flow chart of Fig. 1a, and explained in more detail below.

First, the daily burned area data (500 m resolution) were reprojected to the native SEVIRI imaging grid (3 km resolution at nadir). Because of the uncertainty of the burn date in the burned area product (Boschetti et al., 2010; Giglio et al., 2013), and the fact that a fire can burn multiple days, we followed Roberts et al. (2011) and assumed that all FRP detections within one week of the burned area observations (before or after; i.e., in total 15 days) in a given grid cell belonged to the same fire. Roberts et al. (2011) investigated the distribution of active fire detections in the days around the “day of burn” as determined by the burned area data set and showed that >80% of the SEVIRI active fire detections occurred within 2 days before or after the day of burn, after which the sensitivity rapidly decreases. Using a 15 day time window thus includes nearly all FRE that can be associated with a given fire, while the possible effect of small fires with observed FRP but without corresponding burned area (burning within the same pixel and time window) on the fuel consumption estimates is likely small. Grid cells having only burned area observations but no corresponding FRP detections are likely related to fires having relatively low FRP or those that were obscured by clouds (Roberts et al., 2011). These areas (3% of annual burned area) were excluded from our analysis. Moreover, about half (54%) of the burned area detections showed over 20% cloud cover and/or missing data during the 15 day accumulation period possibly reducing FRE estimates. We decided not to exclude these data to maintain as large a sample as possible but we investigated the impact of this effect via a comparison of results including and excluding partial cloud cover and missing data.

As a second step, the 15 minute interval SEVIRI FRP detections were integrated over time to calculate FRE. This FRE was then converted into dry matter burned using the conversion factor (0.~~356~~368 kg MJ^{-1}) based on lab experiments of various fuel types by Wooster et al. (2005). We limited the study to the spatial distribution of mean fuel consumption and calculated fuel consumption (*FC*) for each 0.25° grid cell (*x,y*) based on:

$$FC(SEVIRI)_{x,y} = \frac{\sum_{2010}^{2014} DM\_burned_{x,y}}{\sum_{2010}^{2014} BA_{x,y}} \quad (1)$$

Where $\sum_{2010}^{2014} DM\_burned$ corresponds to the sum of dry matter burned of each SEVIRI grid cell within the coarser 0.25° grid over the study period with a corresponding burned area observation, and $\sum_{2010}^{2014} BA$ is the sum of burned area (BA) for each 0.25° grid cell with corresponding FRE over the study period.

3.2 Converting MODIS FRP to fuel consumption using in situ measurements

With approximately four daily overpasses, MODIS provides only a sample of daily fire activity and FRP. Various approaches have been developed to derive FRE (Joules) and dry matter burned (kg) estimates from the MODIS FRP data (e.g., Ellicott et al., 2009; Freeborn et al., 2009, 2011; Vermote et al., 2009; Kaiser et al., 2012). However, methods to convert MODIS FRP to FRE usually work at the relatively coarse spatial and/or temporal scale (e.g., 0.5° monthly) required to accumulate a statistically valid number of FRP observations. The sensitivity of the MODIS burned area product to 'small fires' is considerably worse than that of the MODIS active fire product (Randerson et al., 2012), and within each relatively large grid cell the proportion of FRP observations that originate from these small (unmapped) burned areas remains unknown. Therefore, these methods cannot directly be used to estimate fuel consumption. The method developed here to derive FRE is similar to the one used within the GFAS version 1 (Heil et al., 2010; Kaiser et al., 2012), but observations of 'small fires' (having FRP detections but no corresponding burned area) were discarded (by working at the native MODIS 1 km resolution). Because the objective here was to estimate fuel consumption per unit area burned instead of total dry matter burned, the impact of ignoring the smallest fires is small, as long as fuel consumption in such fires is of a similar magnitude or their relative fraction is low. An overview of the method is shown in the flow chart of Fig. 1b, and explained in more detail below.

As with the approach detailed in Sect. 3.1, the daily MODIS burned area data (500 m resolution) was rescaled to the resolution of the active fire product (for MODIS a 1 km resolution). Also, all MODIS FRP detections within a week before or a week after a 1 km grid cell was flagged as 'burned' were assumed to be part of the same fire. FRP detections without corresponding burned area within this period were assumed to correspond to small fires and were excluded from the analysis. In contrast to the approach based on SEVIRI data, here all burned area observations were included. The FRP detections made by the MODIS instruments are more sensitive to small fires than the burned area product (Randerson et al., 2012), and it can therefore be reasonably assumed that the vast majority of fires that leave a detectable burned area signal will be observed by the MODIS instruments if there is a MODIS detection opportunity (i.e., a non-cloud obstructed overpass of one of the MODIS instruments) during the fire.

The FRP recorded by the polar orbiting MODIS instruments are affected by the MODIS scan geometry (Freeborn et al., 2011), cloud cover, tree cover (Freeborn et al., 2014b), and the fire diurnal cycle and daily number and timing of overpasses (Andela et al., 2015). Hence, whilst a single MODIS FRP detection is somewhat representative of the overall fire activity in a certain grid cell, its value is also influenced by these other factors (e.g., Boschetti and Roy, 2009; Freeborn et al., 2009; Andela et al., 2015). Moreover, temporal variations in fuel consumption may be considerable, driven by climate, vegetation type, management, and fire return periods (Shea et al., 1996; Hély et al., 2003b; Savadogo et al., 2007). Minimising the impact of these ~~type~~types of perturbations is in part why methods developed to estimate FRE from MODIS FRP generally require the accumulation of MODIS FRP observations over relatively coarse spatiotemporal scales (e.g., Freeborn et al., 2009; Vermote et al., 2009). We further investigated the combined effect of all these factors on the FRP data by studying the distribution of FRP-observations for a frequently burning grid cell in Africa.

Following the methods applied within GFAS (Heil et al., 2010; Kaiser et al., 2012), FRE was estimated by assuming that the observed daily fire activity (i.e., FRP) at cloud free MODIS overpasses is representative for daily fire activity. To create a sufficiently large and 'representative' sample size, burned area detections and FRP detections with corresponding burned area were aggregated to a 0.25° spatial resolution for the full period that both Aqua and Terra were in orbit (2003 – 2014). Subsequently the total emitted FRE (J) over the study period was calculated per grid cell as the sum of FRP (Watt or J s^{-1}) multiplied by the mean duration between two MODIS detection opportunities (s) during the burning season (calculated using the mean number of cloud free overpasses per day weighted by monthly burned area). This way we implicitly correct for variation in the daily detection opportunity caused by cloud cover and/or the MODIS orbits (e.g., Kaiser et al., 2012; Andela et al., 2015). For further analysis we only include those 0.25° grid cells containing at least 50 MODIS FRP detections (together responsible for 96% of annual burned area).

~~Because~~Similar to the method based on the SEVIRI data we used the 0.368 Kg MJ^{-1} conversion factor to derive fuel consumption (Wooster et al., 2005). However, because of the uncertainties in the FRE estimates, we calibrated our results ~~directly~~ against field measurements. We used simple linear regression forced through the origin~~, to derive a conversion factor (kg MJ^{-1})~~ between the uncorrected MODIS-derived ~~FRE per unit area burned (MJ~~fuel consumption (kg m^{-2}) and the corresponding field measurements of fuel consumption ~~(kg m^{-2})~~ compiled by van Leeuwen et al. (2014)~~.~~, to derive a correction factor between the MODIS-derived FRE per unit area burned (MJ m^{-2}) and the emitted FRE at the Earth's surface. Bootstrapping (n=10,000, bias corrected and accelerated bootstrap) was used to study the uncertainty associated with this correction factor. From ~~this~~the field measurement database we included all measurements conducted in grasslands, savannas and woody savannas (Table 1). The results were also compared to the results based on the approach using the SEVIRI instrument outlined in Sect. 3.1~~, however~~. However, in that case we did not apply the ~~conversion factor as suggested by Wooster et al. (2005) to enable direct comparison~~FRE correction factor, to better understand the impact of the different sensor characteristics and methods used here on the fuel consumption estimates.

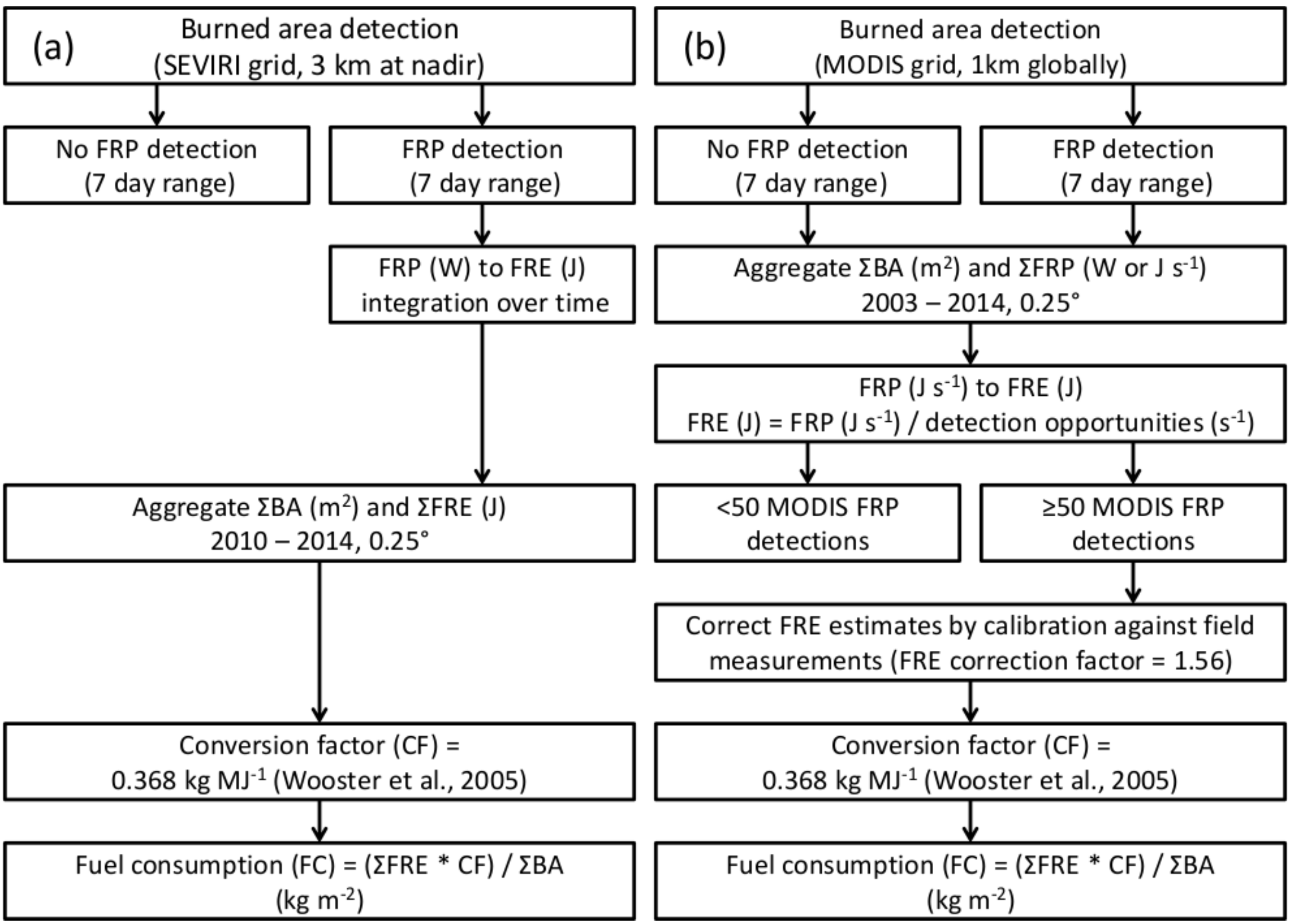

Figure 1. Methods to derive 0.25° fuel consumption estimates based on two different approaches. (**a**) The pathway used to combine FRP data of the geostationary SEVIRI instrument with burned area data to derive fuel consumption (Roberts et al., 2011; Sect. 3.1). (**b**) The pathway used to derive fuel consumption by combining FRP data of the polar orbiting MODIS

instruments with burned area data (Sect. 3.2). Note that FRP detections without corresponding burned area, associated with small fires, are excluded in both processing chains.

4 Results

4.1 Comparing SEVIRI and MODIS-derived fuel consumption

To provide new insights in the specific qualities and limitations of polar orbiting and geostationary based FRP data, we compared the mean fuel consumption (kg m^{-2}) estimates based on our approach using SEVIRI FRP data (Fig. 2a) with our approach using MODIS FRP data (Fig. 2c). Although later on a new conversion factor is derived to convert the MODIS based FRE into DM burnedestimates are calibrated against field measurements, here bothwe use the uncorrected FRE estimates were converted using the same conversion factor (0.356 kg MJ^{-1}; Wooster et al., 2005) for comparisonto provide insights in the effect of sensor characteristics and our methods on absolute FRE estimates. We used linear regression fitted through the origin (Fig. 2b), to compare the results. Total estimated FRE, and thus fuel consumption, based on the MODIS instruments was roughly two times larger than SEVIRI-derived fuel consumption. On top of these absolute differences, the spatial patterns were not uniform (Fig. 2b and d), for which we identified two main causes: first the MODIS based fuel consumption was consistently higher in south--eastern Africa (e.g., Mozambique and Madagascar), likely because of the decreasing sensitivity of the SEVIRI instrument at the greater off-nadir angle over this region (e.g., Freeborn et al., 2014b); and second the difference between both approaches was larger in areas of infrequent fires (compare Fig. 2d and Fig. A1a), possibly explained by the relatively short and slightly different periods of data availability (SEVIRI 2010 – 2014; MODIS 2003 – 2014) in combination with large inter-annual variations in fuel consumption (e.g., Hély et al., 2003b).relative fraction of FRE emitted during periods that FRP values were below the SEVIRI detection threshold, a function of the absolute FRP values and the shape of the fire diurnal cycle. Fires with high FRP (related to high fire spread rates and/or fuel consumption) are often equally well observed by both instruments (i.e., red color in Fig. 2d), while areas with low fuel consumption are often characterized by a larger differences between the MODIS and SEVIRI estimates (i.e., green color in Fig. 2d). To prevent these differences from affecting our estimated correlation too much, we only included frequently burning grid cells (burned area ≥ 15 % yr^{-1}) and those having a surface area of the SEVIRI FRP-PIXEL product grid cells below 12 km^2 (minimum value is 9 km^2 at nadir) during the linear regression shown in Fig. 2b. This resulted in reasonable correlation (r^2 = 0.42; n = 66216569). Partial cloud cover and missing data were also affecting the analysis, and we found that 54% of the annual burned area occurred during periods of reduced data availability (below 80%).% during the 15 day time window). When excluding these events, the absolute difference between MODIS and SEVIRI based fuel consumption became somewhat smaller (i.e., the slope in Fig. 2b became 0.6159), demonstrating that periods of reduced observations were partly responsible for the underestimation in SEVIRI-derived fuel consumption. However, by excluding this 54% of the data, the correlation between MODIS and SEVIRI based fuel consumption was reduced (r^2=0.3128), due to the heterogeneous nature of fuel consumption.

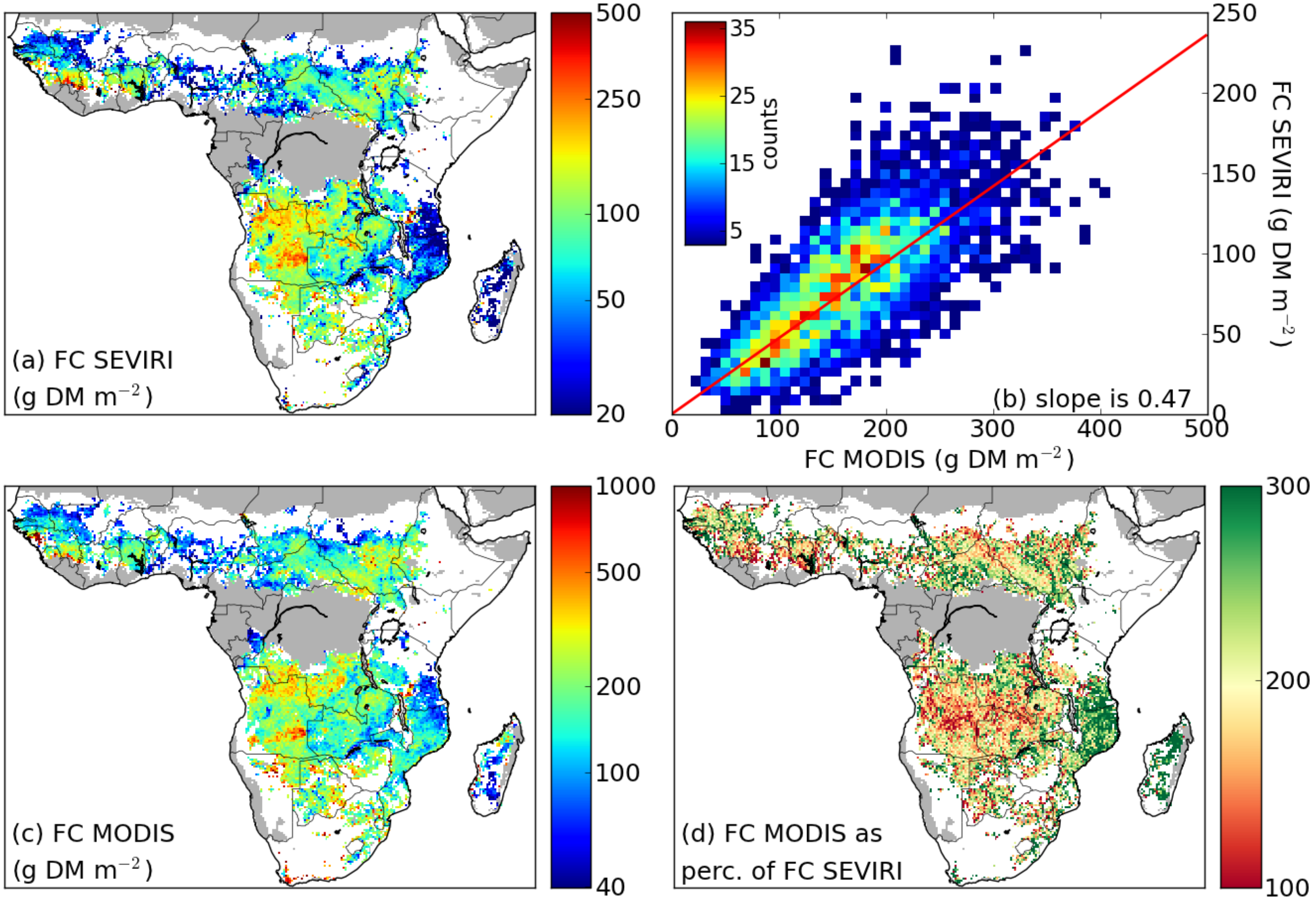

Figure 2. Comparison of fuel consumption (FC) estimates derived by combining FRP and burned area data. (**a**) Fuel consumption derived using SEVIRI FRP data. (**b**) Correlation between fuel consumption estimates based on the SEVIRI and MODIS FRP data. (**c**) Fuel consumption derived using MODIS FRP data. (**d**) MODIS based fuel consumption estimates as percentage of the SEVIRI based estimates. ~~In both cases FC was derived using the same 0.368 kg MJ^{-1} conversion factor (Wooster et al., 2005). Grid cells with dominant land cover ‘forest’ or ‘bare or sparsely vegetated’ were excluded from our analysis and are masked grey, while water and grid cells with less than 50 MODIS FRP detections during our study period (2003 – 2014)~~ For comparison both SEVIRI and MODIS based estimates are shown for the same period (2010 – 2014) and the MODIS FRE data is uncorrected (see Sect. 4.2). Note that on average MODIS-derived FC is about twice as large as SEVIRI-derived FC. Grid cells with dominant land cover ‘forest’ or ‘bare or sparsely vegetated’ were excluded from our analysis and are masked grey, while water and grid cells with less than 50 MODIS FRP detections are shown in white in all figures.

4.2 Converting MODIS FRP to fuel consumption using in situ measurements

~~Although the FRE per unit area burned can be converted to fuel consumption using the conversion factor found by Wooster et al. (2005) during laboratory experiments which we have used so far, some instrument~~Instrument specific issues may ~~further affect the~~ have a large effect on FRE estimates ~~from space (see~~based on satellite remote sensing (see Sect. 4.1 and methods). In order to correct for uncertainties in the MODIS derived FRE estimates, we derived ~~an alternative conversion~~a FRE correction factor (1.56) by comparing the uncorrected MODIS ~~FRE per unit area burned directly~~ derived fuel consumption to field measurements ~~instead~~ (Fig. 3a). ~~This way, we found a conversion factor of 0.572 kg MJ^{-1}, about 1.5 times higher than the conversion factors of 0.368 kg MJ^{-1} based on the laboratory experiments (Wooster et al., 2005).~~ Due to the limited number of field observations and a number of outliers, the bootstrapped 95% confidence interval of the correction factor ranges from 1.30 to 1.80. In addition the coefficient of determination (r^2) between both data sets is considered reasonable (0.41), something we return to in the discussion.

Figure 3b shows the distribution of MODIS FRP detections for a frequently burning 0.25° grid cell in northern Africa for the 2003 – 2014 study period. As discussed in the methods, a single MODIS FRP detection is often not representative for the actual fuel consumption rate or fire activity, and it is more ~~reasonably~~reasonable to take a representative sample (we used a minimum of 50 active fire pixel detections). For this particular 0.25° grid cell (Fig. 3b), over the full period there were 967 MODIS FRP detections, having a sum of 39.7 GW, while total burned area was 5.7×10^9 m^2. During the burning season, the two MODIS instruments together observed the grid cell 2.8 times a day on average. The estimated FRE per unit area burned was therefore 0.22 MJ m^{-2}. ~~Using~~After applying the ~~conversion~~correction factor of 1.56 derived below (Fig. 3a), the estimated FRE per unit area burned becomes 0.34 MJ m^{-2} and fuel consumption for the grid cell shown in Fig. 3b is ~~124~~125 g DM m^{-2}. To put this value in context, for this grid cell the mean NPP was 732 g DM m^{-2} yr^{-1} and the mean fire return period 1.75 years over the study period.

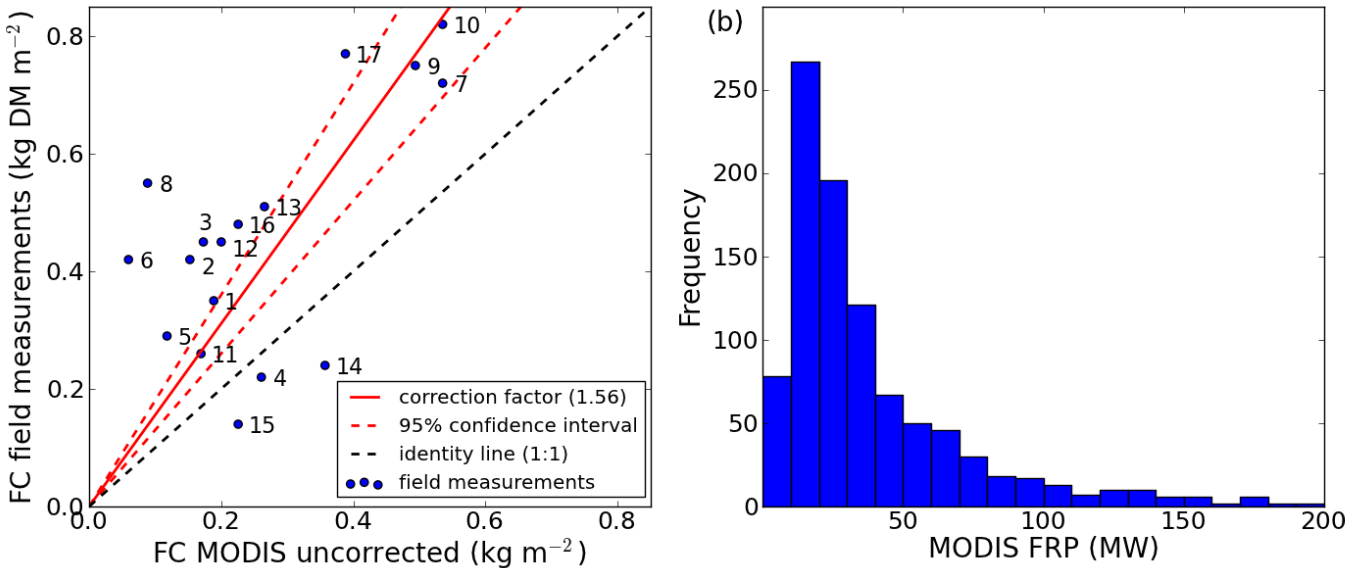

Figure 3. Relationship between MODIS FRP detections and fuel consumption (FC). (**a**) ~~Best estimated conversion factor between~~ Comparison of MODIS derived ~~FRE per unit area burned and~~ fuel consumption without correction for uncertainties in the FRE estimates with field measurements of fuel consumption. The slope between the uncorrected MODIS-derived FC and the FC from field measurements (red line ~~indicates the conversion factor~~, slope is 1.56) is used to correct the MODIS-derived FRE per unit area burned and estimate absolute fuel consumption. The red dashed lines indicate the bootstrapped 95% confidence interval of the slope (1.30 - 1.80), here ~~and the black line the conversion factor found by Wooster et al. (2005) during laboratory experiments~~used as an estimate of uncertainty. The blue dots and numbers refer to the individual field studies (van Leeuwen et al., 2014; Table 1). (**b**) Distribution of MODIS FRP detections (binned in classes of 10 MW wide) for a frequently burning 0.25° grid cell in northern Africa (10.00 – 10.25° N, 24.00 – 24.25° E).

Table 1 provides an overview of the field studies used to calibrate the MODIS based ~~fuel consumption estimate~~FRE estimates (Fig. 3a), and corresponding 0.25° fuel consumption estimates based on MODIS FRP detections. Most fuel consumption estimates based on field measurements are similar in magnitude to the ones derived here, although there are a few prominent outliers (~~Ref.~~numbers 6, 8, 14 and 15). The field studies corresponding to ~~Ref.~~numbers 15 and 16 were carried out within the same 0.25° grid cell and illustrate that individual case studies are not always directly comparable with our 0.25° fuel consumption estimates due to the large spatial heterogeneity of fuel consumption.

Table 1. Fuel consumption estimates for grasslands, savannas and woody savannas, based on field studies compiled by van Leeuwen et al. (2014) and the corresponding 0.25° fuel consumption estimates derived here. For the field studies, numbers in parentheses show the standard deviation. N is the number of active fire detections by MODIS (2003 – 2014) for each 0.25° grid cell. ~~References: (1,2,3); (4) Hoffa et al. (1999); (5) Hély et al. (2003a); (6) Savadogo et al. (2007); (7) Ward et al. (1992); (8) Bilbao and Medina (1996); (9) Miranda et al. (1996); (10) De Castro and Kauffman (1998); (11) Barbosa and Fearnside (2005); (12) Cook et al. (1994); (13) Hurst et al. (1994); (14) Rossiter-Rachor et al. (2008); (15) Russell-Smith et al. (2009); (16) Meyer et al. (2012); (17) Prasad et al. (2001).~~

~~Ref.~~No. Fig. 3a	Lat.	Lon.	FC (g DM m^{-2}) Field study	FC (g DM m^{-2}) MODIS	N	Description	Reference
1	25.15 S	31.14 E	350 (140)	294	226	Lowveld sour bushveld savanna	Shea et al. (1996) and Ward et al. (1996)
2	12.35 S	30.21 E	420 (100)	237	1487	Dambo, miombo, chitemene	Shea et al. (1996) and Ward et al. (1996)
3	16.60 S	27.15 E	450 (–)	269	216	Semi-arid miombo	Shea et al. (1996) and Ward et al. (1996)
4	14.52 S	24.49 E	220 (120)	405	880	Dambo and miombo	Hoffa et al. (1999)
5	15.00 S	23.00 E	290 (90)	183	407	Dambo and floodplain	Hély et al. (2003a)
6	12.22N	2.70 W	420 (70)	92	177	Grazing and no grazing	Savadogo et al. (2007)
7	15.84 S	47.95 W	720 (90)	832	126	Different types of cerrado	Ward et al. (1992)
8	8.56 N	67.25 W	550 (190)	138	232	Protected savanna for 27 years	Bilbao and Medina (1996)
9	15.51 S	47.53 W	750 (–)	768	69	Campo limpo and campo sujo	Miranda et al. (1996)
10	15.84 S	47.95 W	820 (280)	832	126	Different types of cerrado	De Castro and Kauffman (1998)
11	3.75 N	60.50 W	260 (90)	263	35	Different types of cerrado	Barbosa and Fearnside (2005)
12	12.40 S	132.50 E	450 (130)	311	1885	Woodland	Cook et al. (1994)
13	12.30 S	133.00 E	510 (–)	413	1277	Tropical savanna	Hurst et al. (1994)
14	12.43 S	131.49 E	240 (110)	555	433	Grass and woody litter	Rossiter-Rachor et al. (2008)
15	12.38 S	133.55 E	140 (160)	351	1357	Early and late season fires	Russell-Smith et al. (2009)
16	12.38 S	133.55 E	480 (–)	351	1357	Grass and open woodland	Meyer et al. (2012)
17	17.65N	81.75 E	770 (260)	603	20	Woodland	Prasad et al. (2001)

Fuel consumption for the three study regions was derived by applying the ~~conversion~~correction factor (Fig. 3a; ~~0.572 kg MJ^{-}~~1.56) to the FRE per unit area burned (MJ m^{-2}) as estimated using the MODIS FRP-detections ~~(~~over the full period study period (2003 – 2014; Fig. 4). South America generally showed relatively high fuel consumption, with the fringes of the deforestation areas having by far the highest values (Fig. 4a). Sub-Saharan Africa has relatively low fuel consumption compared to Australia and southern America, with lowest fuel consumption found in East Africa and agricultural regions in western Africa (e.g., Nigeria; cf. Fig. 4b and Fig. A1h). Australia shows a surprising pattern where fuel consumption according to our approach in frequently burning savannas in northern Australia appears to be lower than fuel consumption in the drier interior (Fig. 4c and Fig. A1c). The same pattern is observed in some arid regions of southern Africa where fires have long return periods (e.g., Namibia; Fig. 4b and Fig. A1b).

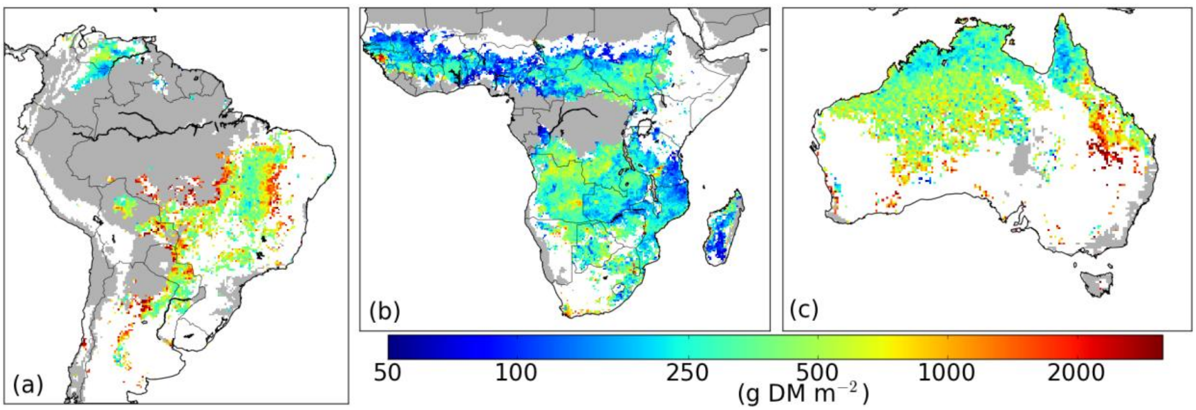

Figure 4. Distribution of fuel consumption based on MODIS ~~FRP-detections and the conversion factor~~ derived ~~from~~FRE per unit of area burned (2003 – 2014) and calibrated against field studies. (**a**) South America, (**b**) Sub-Saharan Africa and (**c**) Australia.

4.3 Drivers and dynamics of fuel consumption

For each continent we assessed whether most fires occurred in productive or low productivity systems, and whether short or long fire return periods were most common (Fig. 5a – c). Then we explored the distribution of fuel consumption as a function of productivity and fire return periods (Fig. 5d – f), followed by the possible role of land cover type in explaining these patterns (Fig. 5g – i). We found that biomass burning on the three continents occurred under very different conditions in terms of productivity and fire return periods. Within the South American study region most fires occurred in relatively productive savannas (NPP of 800 – 1600 g DM m^{-2} yr^{-1}) and were characterized by relatively long fire return periods (3 – 8 yrs). Fuel consumption in this region was higher than under similar conditions (in terms of NPP and fire return period) in Sub-Saharan Africa and Australia. African biomass burning was dominated by (woody) savanna fires of annual and biennial return periods which were observed over a wide range of NPP (500 – 2000 g DM m^{-2} yr^{-1}). For the lower productivity African savannas and grasslands, we did not find large differences in fuel consumption between savannas that burn annually or biennially, and savannas with somewhat longer return periods (3 – 8 yrs). Only African savannas with fire return periods above 8 years showed again a somewhat higher fuel consumption. Strikingly, in the more productive African savannas fuel consumption declined with longer fire return periods.

In Australia most burned area occurred in the savannas of intermediate productivity (500 – 1200 g DM m^{-2} yr^{-1}) and low productivity Hummock grasslands (<500 g DM m^{-2} yr^{-1}; Australian Native Vegetation Assessment, 2001), that were classified as shrublands by the MODIS land cover dataset. While in Sub-Saharan Africa most fires in the lower productivity regions were fuelled by grasses that form well connected fuel beds, in Australia most fires occurred in poorly connected Hummock grasslands that functionally act like shrublands. Both in Sub-Saharan Africa and in Australia regions classified as shrubs faced longer fire return periods than grasslands and savannas, but eventually burned with higher fuel consumption. But even when productivity and fire return periods were similar the fuel consumption in the low productivity (<500 g DM m^{-2} yr^{-1}) Hummock grasslands of Australia was consistently higher than fuel consumption of the low productivity grasslands in Sub-Saharan Africa.

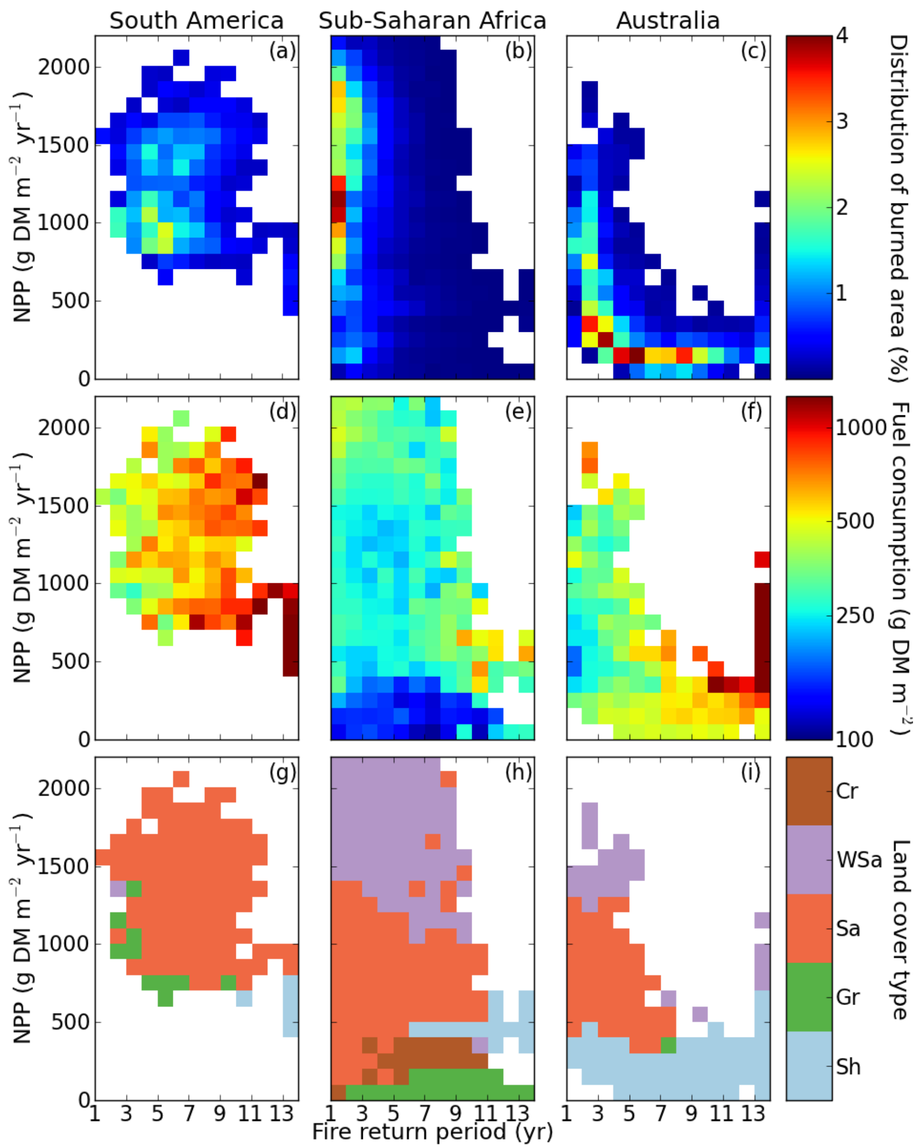

Figure 5. Distribution of burned area (**a-c**), fuel consumption (**d-f**) and dominant land cover type (**g-i**), all binned as a function of fire return periods and net primary productivity (NPP) for the three study regions (South America, Sub-Saharan Africa and Australia). Bins with burned area below 500 km^2 yr^{-1} are masked in white. Abbreviations of land cover type stand for: cropland (Cr), woody savanna (WSa), savanna (Sa), grassland (Gr) and shrubland (Sh).

Finally, we compared the fuel consumption estimates derived from the MODIS FRP-detections (Fig. 4) with fuel consumption estimates of GFED4s. Considerable differences were found between the two approaches (Fig. 6). The fuel consumption estimates derived here resulted in higher fuel consumption estimates for areas of lower productivity, especially those areas dominated by shrublands; while fuel consumption estimates of GFED4s were generally higher in woody savannas, with higher productivity. Interestingly, the best comparison was found in zones of most frequent fire and short fire return periods (compare Fig. 6 with Fig. A1a – c).

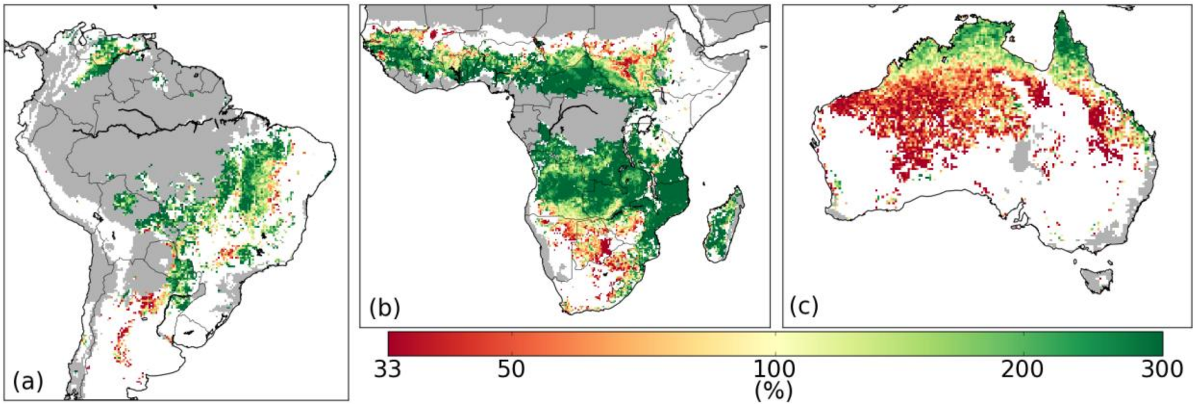

Figure 6. Fuel consumption estimated by GFED4s as a percentage of fuel consumption derived here (based on MODIS derived FRE, calibrated against in situ measurements). (**a**) South America, (**b**) Sub-Saharan Africa and (**c**) Australia.

5 Discussion

Understanding the global distribution of fuel consumption per unit area burned, here referred to as fuel consumption for brevity, and fuel build up mechanisms is important to make landscape management decisions, understand the implications of changes in climate or vegetation patterns on fire dynamics, and to derive accurate fire emission estimates. Boschetti et al. (2009) and Roberts et al. (2009, 2011) showed that fuel consumption ~~per unit burned area~~ estimates can be derived from combining burned area and active fire satellite products. Here we build upon their approaches and derived fuel consumption estimates for regions of low tree cover in South America, Sub-Saharan Africa and Australia, and explored the drivers of the spatial distribution. Following previous studies, we found that fuel consumption is highly heterogeneous (e.g., Hély et al., 2003b; Savadogo et al., 2007; Boschetti and Roy, 2009; Roberts et al., 2011). Consequently, obtaining representative field measurements is labour intensive, and only a limited number of studies have been carried out (van Leeuwen et al., 2014). Satellite-derived estimates of the spatial distribution of fuel consumption can therefore form an important addition to the scarce field measurements and may guide future field campaigns.

Here we discuss the pros and cons of the fuel consumption estimates presented in this paper and the current challenges for such an exercise (Sect. 5.1). We then discuss the drivers of fuel consumption in the three study regions, and compare the results found here to fuel consumption estimates of the GFED4s data (Sect. 5.2).

5.1 Satellite-derived fuel consumption estimates

In this study we explored the distribution of fuel consumption beyond the geostationary position of the SEVIRI instrument, and developed a method based on FRP detections of the polar orbiting MODIS instruments. Both geostationary and polar orbiting instruments have advantages, the geostationary SEVIRI instrument observes the full fire diurnal cycle, while the polar orbiting MODIS instruments only providesprovide observations at certain fixed hours of the day, potentially leading to structural errors in the FRE estimates (Ellicott et al., 2009; Vermote et al., 2009; Freeborn et al., 2011; Andela et al., 2015). However, the sensitivity of the MODIS instruments to small fireand more weakly burning fires is much larger than that of the SEVIRI instrument (Freeborn et al., 2014b). In order to get a better understanding of the implications of these differences we compared the fuel consumption estimates based on both platforms using the FRE-to-DM-burned conversion factor found during laboratory experiments (Wooster et al., 2005). At first sight, very similar spatial patterns were found using polar orbiting or geostationary data, (compare Fig. 2a and c), providing confidence in the spatial distribution of the fuel consumption estimates. However, many differences were also present (Fig. 2d). We found that a large part of the differences could be attributed to: (i) the large natural temporal variation in fuel consumption combined with the different periods of data availability and (ii) the different sensors characteristics and methods used here. The shape of the fire diurnal cycle for example affects both MODIS based fuel consumption estimates due to the limited number of daily overpasses but also the SEVIRI derived fuel consumption estimates because it directly affects the relative fraction of daily fire activity that falls below the SEVIRI detection threshold. After excluding grid cells at higher off-nadir angles of the SEVIRI instrument and of infrequent fire occurrence, we found an r^2 of 0.42 between both approaches. Other potential sources of spatial discrepancy, like the fire diurnal cycle, were smaller. Finally, a large structural difference was observed, and SEVIRI-derived fuel consumption was about half of the MODIS-derived fuel consumption. Such structural differences likely occur due to the different sensitivities of the instruments (Freeborn et al., 2009, 2014b). As compared to the MODIS instruments, the SEVIRI instrument likely underestimates fire activity in areas where a relatively large fraction of fire activity falls below the detection threshold (e.g., small fires, or fires partly obscured by trees; as discussed by e.g., Roberts and Wooster, 2008; Freeborn et al., 2009, 2014b; Roberts et al., 2011). In our analysis a small part of the structural difference could also be explained by the fact that we did not correct for cloud cover and/or missing data in the SEVIRI based FC estimates. Not surprisingly, the best comparison between both methods was found in areas of frequent fireshigh fuel consumption rates (Fig. 2d and A1)), for example areas where fires oftencan spread over large areas to form large fire fronts (Archibald et al., 2013), and are thusareas of high fuel consumption, these fires with high FRP are likely to be well observed by both instruments.

When deriving fuel consumption estimates based on the SEVIRI instrument, Roberts et al. (2011) found fuel consumption estimates around 3.5 times lower than modelled values of GFED3.1 (van der Werf et al., 2010). Other studies that calculated fire emissions using the SEVIRI instrument found similar low estimates compared to GFED (e.g., Roberts and Wooster, 2008). Following previous studies, we find that about half of this discrepancy can be attributed to SEVIRI failing to detect the more weakly burning~~, but highly numerous, smaller~~ fires that ultimately are responsible for around half of the emitted FRE (Freeborn et al., 2009, 2014b). ~~However, other sensor specific aspects also affect the~~ Similarly, MODIS-derived FRE estimates ~~(see Methods).~~are also affected by the sensor characteristics and methods used here. We therefore decided to ~~relate~~correct for such issues by calibrating the FRE per unit area burned based on the MODIS instruments directly ~~to~~against field observations ~~to convert~~before converting them to ~~measures of~~ fuel consumption. ~~We used~~When using the conversion factor found by Wooster et al. (2005) and the uncorrected MODIS FRE estimates, a slope of 1.56 was found during linear regression between MODIS derived fuel consumption ~~database~~and fuel consumption estimates based on field measurements (Fig. 3a). Because of ~~van Leeuwen et al.~~ the large spatiotemporal variation in fuel consumption and the relatively low sample size, the 95% confidence interval of the bootstrapped correction factor was 1.30 - 1.80. The uncertainty associated with the correction factor is thus around plus or minus 16%, although other factors may further affect the uncertainty of our fuel consumption estimates as discussed below. The need for a FRE correction factor (1.56) may for a large part be explained by sensor specific limitations ~~(2014)~~(Giglio et al., 2006a)~~ and the recommendation therein to use linear regression rather than biome mean values to derive the conversion factor. The conversion factor found using the field observations (Fig. 3; CF = 0.572 kg MJ^{-1}) was still around 1.5 times larger than the one found by Wooster et al. (2005; CF = 0.368 kg MJ^{-1}). This may for a large part be explained by sensor specific limitations, for example the lower~~ that likely lead to underestimations of total FRE, particularly due to the reduced sensitivity of the MODIS instruments towards the swath edges (Freeborn et al., 2011). The fire diurnal cycle in combination with the timing of the MODIS overpasses and partial cloud cover may also have affected absolute FRE estimates and thus the ~~conversion~~FRE correction factor derived here (Andela et al., 2015).~~ Directly applying the conversion factor found by Wooster et al. (2005) on the MODIS derived FRE per burned area as derived here would therefore lead to an underestimation of fuel consumption (Fig. 3a). However~~ Although Freeborn et al. (2011) find a similar correction to be needed due to the decreasing sensor sensitivity with increasing scan angle, the number of field measurements was limited and our calibration was strongly influenced by a few field studies in more productive savannas. The correlation of the field observations and the 0.25° long term average fuel consumption estimates derived here (Fig. 3a; r^2=0.41) was affected by various factors. Most importantly, fuel consumption is both spatially and temporarily highly heterogeneous (e.g., Hoffa et al., 1999; Hély et al., 2003b; Govender et al., 2006), so even in the case of accurate fuel consumption estimates from both field measurements and from satellite, large scatter is likely observed. ~~In addition, direct comparison~~In addition, the fuel consumption estimates derived here are mostly representative for mid-day burning during the peak burning season because FRE emitted during these periods will dominate the signal. Finally, direct comparison with the field studies was impossible because most field studies were carried out before the launch of the MODIS and SEVIRI instruments (van Leeuwen et al., 2014).

Given the large scale at which landscape fires occur and the high spatiotemporal variation in fuel consumption, satellite-derived fuel consumption estimates are crucial to get a better system understanding. While different satellite-derived fuel consumption estimates resulted in a similar spatial distribution, the absolute fuel consumption estimates remained more uncertain. This study clearly demonstrated the potential to derive fuel consumption estimates by combining satellite derive FRP and burned area. However, deriving accurate FRE estimates is difficult due to several sensor specific limitations. Here we choose to calibrate against field observations, correcting for such errors. Better understanding of for example the effect of tree cover on FRP detections would allow for expansion of such methods beyond open land cover types. Validation of the satellite-derived products by specifically designed field campaigns aiming for example at NPP or fire return period transects, or high resolution airborne remote sensing may further improve our understanding of the active fire sensor characteristics and provide more confidence in absolute fuel consumption estimates in the future.

5.2 Drivers and dynamics of fuel consumption

Fuel consumption depends on the amount of fuel available for burning and the combustion completeness. In arid areas available fuel and thus fuel consumption is often limited by precipitation. Across these arid and semi-arid areas precipitation generally determines vegetation productivity and tree cover. Grasses in these more arid ecosystems often have a combustion completeness above 80% (van Leeuwen et al., 2014), and fuel consumption and fuel loads will generally be similar. In more humid regions, however, fuel moisture may limit fuel consumption by lowering fire spread and the combustion completeness (Stott, 2000; van der Werf et al., 2008). Consequently savannas of intermediate NPP and with a clear dry season tend to burn most frequently (Bowman et al., 2009). In our three study regions (South America, Sub-Saharan Africa and Australia) fires occurred under very different conditions in terms of NPP and fire return periods (Fig. 5a – c), partially as a result of the different distributions of NPP across the study regions. In South America most burned area occurred in regions with fire return periods between 3 – 8 years and intermediate productivity (800 – 1600 g DM m^{-2} yr^{-1}). In Africa the vast majority of burned area was found in areas with short fire return periods (1 – 3 yrs) and a wide range of productivity (500 – 2000 g DM m^{-2} yr^{-1}). And inIn Australia the majority of fires occurred in the more arid low productivity zones (<500 g DM m^{-2} yr^{-1}) while annually burning regions were uncommon and restricted to the humid higher productivity zones (typical fire return periods were in the range 2 to 10 years). Although climate and vegetation shape the boundary conditions for fires to occur, most ignitions are of human origin (Scholes and Archer, 1997; Stott, 2000; Scholes et al., 2011; Archibald et al., 2012) and the differences between the continents are expected to be partly the result of different management practices. Overall, a pattern of increasing fuel consumption towards more productive regions and longer return periods was observed (Fig. 5d – f). Consequently fuel consumption in Africa, with short return periods, was relatively low compared to Australia or Southern America. However, increases in fuel consumption with increasing time between fires and NPP were far from linear and other drivers also played a large role (e.g., Shea et al., 1996). Most notably.

In more arid regions, we found a clear difference between ecosystems where most fuel exists of grasses opposed to regions that were classified as shrubs. In Africa, the more arid regions with NPP below 500 g DM m^{-2} yr^{-1} are dominated by savannas or grasslands, while in Australia these regions are classified as shrubs (Fig. 5h and i). In the specific case of

Australia, much of the interior is actually dominated by Hummock grasslands (rather than shrubs), grasses that functionally act like shrubs (Australian Native vegetation Assessment, 2001) and are therefore classified as being shrublands in the UMD classification. Grasses may form well-connected fuel beds, resulting in short (often annual or biennial) fire return periods (Scholes and Archer, 1997; Beerling and Osborne, 2006; Archibald et al., 2013), while fire return periods in shrublands (or Hummock grasslands) were generally longer (Fig. 5). But on top of the differences in fire return periods between these low productivity ecosystems, the grass species that were dominant in most of Africa showed a rather slow fuel build up compared to shrubs or the Australian Hummock grasses even when fire return periods and productivity were similar (Fig. 5e and f). A possible explanation for the relatively slow fuel build up in African grasslands and savannas as opposed to Australian Hummock grasslands and shrublands could be grazing by livestock or wildlife and human management (Savadogo et al., 2007; Scholes et al., 2011). Shea et al. (1996) report a large impact of wildlife, ranging from insects to grazers, on fuel build up processes in various study sites in Africa and such effects will differ among continents given that neither South America or Australia have the diverse and dominant mega-herbivore fauna of Africa. Other differences may come from non-fire related decomposition rates, that depend on plant species and climate (Gupta and Singh, 1981).

In the more productive savannas marked differences were observed between the different continents (Fig. 5). Africa was unique when it comes to its short fire return periods, even in highly productive ecosystems. In African savannas of intermediate productivity (500 – 1500 g DM m^{-2} yr^{-1}), fuel build up with time ~~was~~appeared slow compared to the other continents. These differences may originate from differences of grazing pressure or the occurrence of different species, as discussed above, but may also be related to management practices or climate. For example, the highest fuel consumption in the more humid African savannas was found in the most frequently burning grid cells, suggesting ~~both high combustion completeness and high fuel availability.~~a high combustion completeness. In areas where burning is largely limited by fuel humidity, the combustion completeness may have a considerable impact on fuel consumption. The fact that both frequently burning and almost fire free areas occur under similar climatic conditions in (sub)tropical savannas suggest that fuel conditions are important, while frequent fire occurrence may enhance flammability (Shea et al., 1996; Ward et al., 1996). Short fire return periods provide a competitive advantage to herbaceous vegetation over woody vegetation (Bond et al., 2005; Bond, 2008). A high degree of canopy openness will result in more grass covered area and higher dry season ground surface temperatures and lower fuel moisture content resulting in high combustion completeness. However, a similar temperature or moisture driven effect may also be caused by the timing of the ignitions (Hoffa et al., 1999) directly related to management practices. Le Page et al. (2010) showed that African savannas typically burn early in the dry seasons, while Australian savannas often burn later in the season. Finally, the above assumes a stable situation of tree cover density and biomass over the study period, while in some regions there is tree cover loss due to ~~increased~~decreased fire ~~frequency~~return periods or land use change over our relatively short study period, while other areas are experiencing increases in tree cover (Wigley et al., 2010). A clear example was South America, where the apparent fuel build up (Fig. 5d) appears largely driven by high fuel consumption in active deforestation areas (Fig. 4; see Hansen et al., 2013). The effect of human management on fuel loads was also clearly visible in Africa's agricultural areas (e.g., Nigeria) where fuel loads were typically low (Fig. 4 and Fig. 5e and h).

Finally, the fuel consumption estimates derived here were compared to the modelled fuel consumption estimates of GFED4s. Within GFED fuel build up is largely driven by NPP and fire return periods, while biomass build up is distributed over two different pools: herbaceous and woody (van der Werf et al., 2010). This differentiation is important, because in savanna ecosystems most fires burn in the grass layer, leaving the older well established woody vegetation largely untouched (Scholes and Archer, 1997). Fuel consumption estimates derived here and by GFED were comparable in annual or biennial burning savannas (Fig. 6 and Fig. A1a - c). This is encouraging, because from an emissions perspective the modelling of fuel consumption has to be most accurate in areas that burn annually or biennial where little long-term fuel build up takes place. For arid areas in general but especially for shrublands and the Hummock grasslands in Australia, the fuel consumption estimates derived here were considerably larger than the ones estimated by GFED. Part of this difference may be caused by GFED using a universal fuel build up mechanism for all types of grasses and shrublands (van der Werf et al., 2010), which according to our findings seems oversimplified. In fact, Hummock grasses act like shrubs with bare soil between the mounds of hummock grass (Australian Native vegetation Assessment, 2001), such behaviour likely results in very different fuel build up dynamics which may vary strongly depending on the wet season intensity as opposed to other grasses that form a well connected fuel bed. ~~These results confirm~~The enhanced fuel consumption in arid and semi-arid drylands found here confirms the important role of arid and semi-arid drylands in the inter-annual variability of the global carbon cycle (Poulter et al., 2014).

In more humid regions, with higher woody cover, the fuel consumption estimates of GFED4s were higher than the ones derived here. Within GFED it is assumed that the amount of woody vegetation burned is a function of tree cover within savannas and woody savannas (van der Werf et al., 2010). It remains unclear to what extent the woody vegetation in savannas burns. Although fires greatly reduce the occurrence of trees in many savannas (Bond et al., 2005; Bond, 2008), field studies often report that the established woody vegetation in savannas is rather resistant to fire (Scholes et al., 2011). The potential tree cover for a given area is directly related to mean annual precipitation (Sankaran et al., 2005), although further affected by e.g. the occurrence of different species (Lehmann et al., 2014) or availability of nutrients (Bond, 2008). In the tropics highest precipitation is generally found with decreasing dry season duration and may thus prevent fires from spreading to the woody fraction of the vegetation. Moreover, typical architecture of savanna trees varies considerably between continents affecting their sensitivity to fire (Lehmann et al., 2014; Moncrieff et al., 2014). While some woody species may be better adjusted to relatively cool frequent fires with low fuel loads, most common in frequently burning and/or well grazed grasslands of Africa, other species are better adjusted to more intense and infrequent fire occurrence. Although fuel consumption estimates based on FRP detections may be affected by tree cover to some extent (Freeborn et al., 2014b), active deforestation areas in South America clearly stand out because of their high fuel consumption. We expect that during future studies satellite-derived fuel consumption estimates may help to differentiate between grass fuelled fires and ~~degradation~~ fires~~,~~ that additionally burn part of the woody cover. Moreover, satellite-derived fuel consumption estimates could be used as a reference for biogeochemical models, while providing improved insights in the underlying processes.

6 Conclusions

Satellite-derived fuel consumption estimates (with units of kg dry matter per m^2 burned) provide a unique opportunity to challenge current understanding of spatiotemporal variation in fuel consumption that to date is mostly based on field studies and modelling. The fuel consumption estimates based on fire radiative power (FRP) data of the geostationary SEVIRI and polar orbiting MODIS ~~fire radiative power (FRP) data~~instruments showed good agreement in terms of spatial patterns, suggesting that these estimates were generally robust. When converting fire radiative energy (FRE) estimates derived from MODIS and SEVIRI to fuel consumption using a ~~universal~~ conversion factor based on laboratory measurements and mapped burned area, fuel consumption estimates based on MODIS FRP data were about twice as high as the ones based on the SEVIRI data. This can likely be attributed to SEVIRI failing to detect large parts of the emitted FRE by more weakly burning~~, but~~ or (highly numerous~~,~~) smaller fires, that ultimately are responsible for around half of the emitted FRE. On top of that, when we calibrated the ~~FRE~~fuel consumption estimates based on MODIS FRP detections ~~directly~~ to field observations, we found that a ~~new conversion~~correction factor ~~that~~of 1.56 was ~~about 1.5 times larger than the one based on laboratory experiments~~needed for them to match. This discrepancy likely stems from underestimation of FRE based on the MODIS instruments, for example related to the decreased sensitivity of the instruments towards the swath edges. Our best estimates of fuel consumption based on MODIS derived FRE using the ~~conversion~~correction factor based on field observations were similar in magnitude as modelled fuel consumption estimates from GFED4s, but discrepancies were found in the spatial patterns. However, the limited number of field studies combined with the high spatiotemporal heterogeneity of fuel consumption complicated the comparison of field studies with long-term coarse scale satellite-derived products, and uncertainty in absolute estimates remained therefore considerable. Field studies especially designed to validate satellite-derived fuel consumption estimates, aiming for example at NPP or fire return period transects, possibly using air-based remote sensing, could improve (confidence in) absolute fuel consumption estimates in the future.

Dominant biomass burning conditions in South America, Sub-Saharan Africa and Australia were highly different in terms of NPP and fire return periods, partly driving fuel consumption patterns. In South America most fires occurred in savannas with relatively long fire return periods, resulting in relatively high fuel consumption compared to the other study regions. In contrast, most burned area in Sub-Saharan Africa stemmed from (woody) savannas that burned annually or biennial with relatively low fuel consumption. Australian biomass burning was dominated by relatively unproductive (Hummock) grasslands with a wide range of fire return periods, while savannas with fire return periods of 2 – 3 years also contributed.

Besides NPP and fire return periods, vegetation type played an important role in determining the fuel build up mechanism. Grasslands favoured short fire return periods and were generally characterized by low fuel build up rates. Shrublands, or grassy species that functionally act like shrubs, on the other hand were generally characterized by longer return periods, but gradual fuel build up occurred over the years eventually leading to higher fuel consumption. Similarly, land management had a marked effect on fuel consumption. In the major deforestation regions of South America, fires consumed woody biomass during the MODIS era, increasing fuel consumption estimates. West African fuel consumption was clearly suppressed in some areas, likely associated with agriculture and/or grazing. These results demonstrate that the modelling of fuel consumption is complex while the relation between climate, vegetation and fuel consumption may vary across the continents depending on for example the presence of certain species. During future investigations satellite-derived fuel consumption estimates may be used as a reference dataset for biochemical models, and help to better understand the interaction between climate, vegetation patterns, landscape management and fuel consumption.

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Appendix A

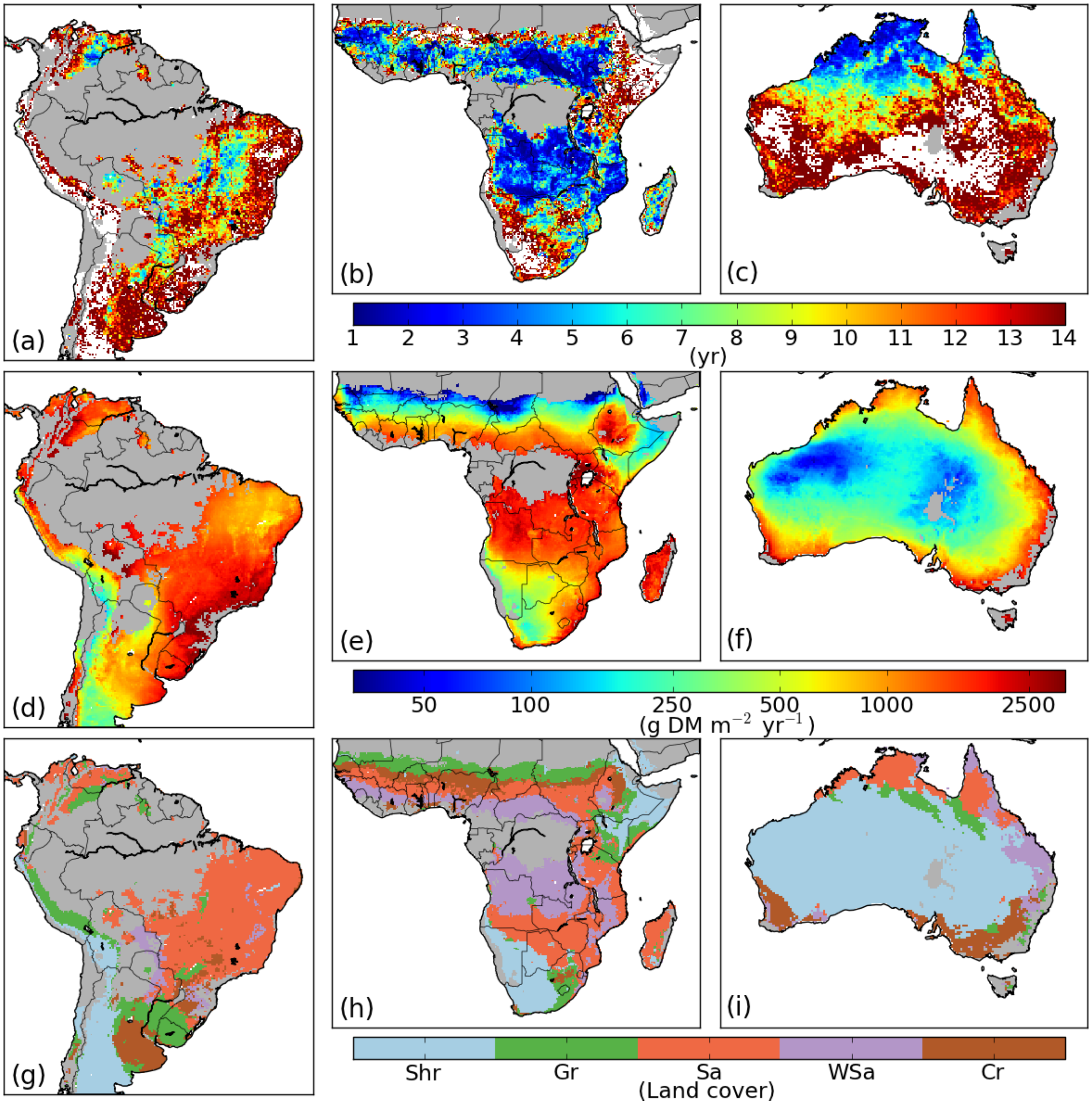

Figure A1. Spatial distribution of parameters affecting fuel consumption dynamics. (**a-c**) Fire return –periods for South America, Sub-Saharan Africa and Australia, respectively; (**d-f**) net primary– productivity for South America, Sub-Saharan Africa and Australia, respectively; and (**g-i**) dominant land cover type for South America, Sub-Saharan Africa and Australia, respectively. Grid cells with dominant land cover 'forest' or 'bare or sparsely vegetated' were excluded from our analysis and are masked grey, while water is shown in white. Abbreviations of land cover type stand for: cropland (Cr), woody savanna (WSa), savanna (Sa), grassland (Gr) and shrubland (Sh).

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