'ASSESSING COMBUSTED BIOMASS FROM SAVANNA FIRES USING SEVIRI GEOSTATIONARY IMAGERY AND COMPARISON WITH THE PRE-BURN BIOMASS AVAILABILITY.'

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Abstract:

We examined the relationship between the combusted biomass and the pre-burn biomass availability for 18 burned grassland savanna areas in Southern Africa. We used SEVIRI FRP data to assess the combusted biomass and the SPOT VGT NPP product to estimate the pre-burn biomass availability. MODIS Level 1b imagery was used for the burned area detection and mapping. A strong linear and highly significant relationship was found ($r^2 = 0.94$, $n = 14$, $p < 0.0001$) between the two variables. For the 18 processed fires, FRE ranged from 0.04 to 23.2 Tjoules combusting 15.5 and 8531.3 tones of biomass respectively. All the fires combusted a total of 38240 tones in a burned area of 270.06 km^2.

Keywords: wildfires, combustion, Fire radiative power, productivity

1. Introduction

A big proportion of the tropical and subtropical areas of Southern Africa is burned every year due to man-ignited fires. This acts as a management tool of local population to prevent trees from prevailing in their grazing areas and to improve the pasture for their cattle (Roy et al., 2005; Grace et al., 2006). Despite the uncertainty on the exact quantities, there is reason to believe that 40% (49% according to van der Werf et al., 2003) of annual CO_2 human related emissions and a quarter of the annual amount of particulate matter are released into the atmosphere through the combustion of biomass at the subtropical savannas and grasslands of southern Africa (Ruiz et al., 2005; Levine, 1996 cited in Smith et al., 2005). According to the same scientists, stratospheric ozone depletion, global warming, and species extinction are all related to human related biomass combustion and its polluting derivatives. Due to this, the need to assess the amount of combusted biomass from these fires has increased significantly. The purpose of this paper is to report a study, the aim of which is to investigate the relation between the pre-burn available biomass and the biomass that was actually combusted during subtropical African savanna fires. To do this, a new multi-sensor approach was applied to burned areas of Zambia, Botswana, Zimbabwe and Namibia. Using MODIS imagery, the burned area for a number of late dry-season fires was detected and mapped. Using Net Primary Productivity (from now NPP) data derived from a SPOT VGT sensor, the carbon and biomass productivity at the locations of the burned areas were assessed. The accumulated biomass for the period that the detected areas were burned was calculated. Using a SEVIRI-derived Fire Radiative Power (from now FRP) dataset for 2004, we calculated the amount of biomass that was actually combusted from the fires at the detected areas. Combustion rates, totals and the temporal character of the events were also examined. A series of products and sensors were used to implement and validate this study and its results. All of them, except the SEVIRI-derived FRP dataset, are publicly available which make this study even more important in terms of applicability and usefulness. The products' compatibility is tested and their limitations are commented upon.

2. Theoretical background

Generally, the amount of combusted biomass is given in equation (1), firstly proposed from Seiler and Crutzen (1980):

$$M = A\beta\rho \tag{1}$$

where M is the fuel mass combusted (kg), A is the burned area (m^2), β is the fuel density (kg m^{-2}) and ρ is the combustion completeness (fraction of fuel that is actually burned).

Recent advances in RS systems and algorithms tend to improve the estimation of the burned area (A) needed in (1) (Wooster et al., 2005). However, according to the same group, the spatial and temporal assessments of (β) and (ρ) are much more difficult to improve. According to Andreae and Merlet (2001), the uncertainty when one estimates combusted biomass via (1) can reach ±50% and for some specific events even more. Due to this, there is need to assess (M) via other methods. Experiments that showed that combusted biomass itself is strongly related to the radiative power of the fire and moreover the two properties fit well in a linear model (Wooster et al., 2005). By monitoring and integrating temporally the FRP of the different thermal components of a given fire, one can estimate the Fire Radiative Energy (FRE) which is directly proportional to the biomass combusted (Kaufman, 1998a; Roberts et al., 2004; Wooster et al., 2004; 2005;). After Wooster et al. (2005), the amount of combusted biomass can be calculated using (2):

$$Fuel\ biomass_{comb}(kg) = 0.368(\pm 0.015) * FRE(MJ) \quad (2)$$

where 0.368 is the factor relating the amount of combusted biomass with Fire Radiative Energy (FRE)

Recently, different research teams used SEVIRI's thermal channels to assess FRP. The Spinning Enhanced Visible and InfraRed Instrument (SEVIRI) is installed onboard the EUMETSAT MSG geostationary satellites. The relatively high altitude limits SEVIRI's spatial resolution. However, having the same evolution time as the Earth and the ability of frequent imaging (every 15 min) with its 8 thermal channels, makes the instrument capable of observing phenomena with strong temporal behaviour such as weather systems, dust storms and fires (Schmetz et al., 2004). Wooster et al. (2005), used exactly this characteristics of SEVIRI sensor to produce an FRP database of the savanna fires that occurred in 2004. It's the same database that we used for this work.

3. Area of study

18 savanna/ grasslands fires were detected and processed in the 2 areas of study which are shown in figure 1. *In the first area of study,* 6 burned areas were detected in North-eastern Namibia, 6 areas in Western Zimbabwe, 2 areas in Northern Botswana and 1 in southern Zambia. *In the second area of study*, 3 areas were detected in Northern Zambia.

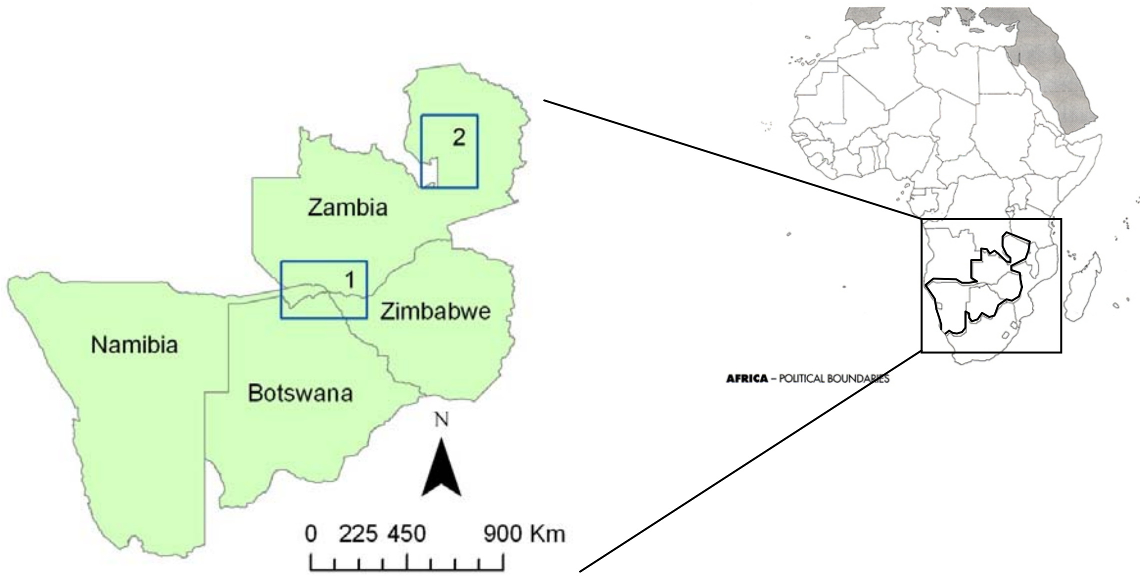


Figure 1. The 2 areas of study shown in blue squares on the left side (Data from DCW, 1993) and their location within the continent on the right side (Source: GEC, 2007, online)

Most of the fires (study area 1) were detected in the area where the borders of 4 countries meet between the Zambezi river in the north and the Chobe National Park of Botswana in the south. The rest of the fires (study area 2) were detected in the Northern and Luapula provinces of Zambia. All of these areas belong to a wider region of Southern Africa which is subject to annual biomass burning (Scholes et al., 1996). The fires in the region are used as a management tool, by the local population, to control the invasion of trees in their grazing fields, and to achieve more nutritious pasture (Roy et al., 2005; Grace et al., 2006). A significant amount of biomass is consumed by cattle and wildlife through grazing. Still, the biggest proportion of the biomass is combusted from the pre-mentioned seasonal fires. Most of the fires occur in the early and late dry seasons, April to July and August to October respectively. The rest of the year is relatively wet and it is at this time that the pre-burn available biomass accumulates.

4. Analysis

4.1 Burned area detection and measurement

For the detection of burned areas, MODIS level 1b (250m) images were retrieved from the LAADS website, covering consecutive days of August 2004. MODIS images are used extensively, for burned area detection and quantification, due to their good overpass frequency, good spectral characteristics and relatively good spatial resolution. According to Sa et al. (2003), MODIS bands 2 (0.86µm - 250m), 5 (1.24µm – 500m) and 6 (1.64µm – 500m) are the most appropriate for burned area detection. In our case, MODIS Band 2 (NIR) was chosen as the most appropriate to quantify the detected areas that were burned during the August 2004 late dry season.

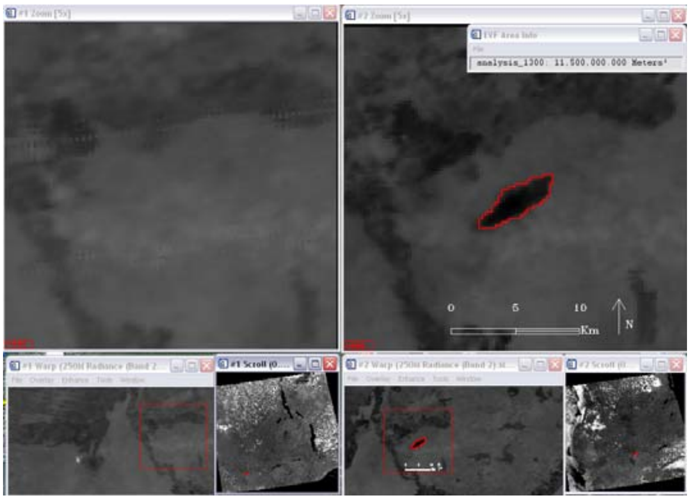
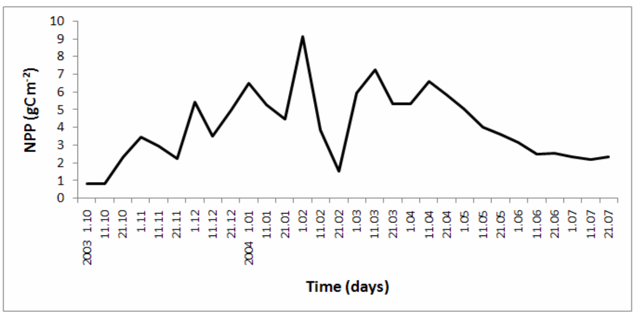


Figure 2. Detection and quantification of an example burned area. On the left display: MODIS band 2 image depicting a burned area on 26/8/2004 just before the fire. On the right display the same area, burned, just after the fire on the 29/8/2004.

4.2 Pre-burn available biomass calculation

For all the 18 detected burned areas, 10-day mean NPP (mgC m^{-2}) values were retrieved from the VITO- GeoSuccess website. For every detected area, the NPP that was retrieved covers the period between August 2004 and the time that the same areas were previously burned (figure 3a and 3b). The GLOBCARBON Burned Area Estimate (BAE) product (VITO, 2007) was retrieved in order to verify the time of the preceding fires for the detected areas. This product comes in monthly estimates of total burned area for specified locations. From the 18 areas, 17 were burned during 2003 dry season and one in 2002. Given the fact that the combustion completeness typically reaches 83 - 98% at the end of the dry-season (Scholes et al., 1996), we assume that the available amount of biomass that is finally combusted, starts to accumulate from the beginning of the growing season (01/10) just after the first fires till the time prior to the fires of August 2004 (21/07). The accumulated carbon production per area was then divided with the Carbon-in-biomass factor (0.48) which is the concentration of carbon in a mass unit of biomass (Zabek and Prescott, 2006) and the accumulated biomass was calculated. The available biomass per detected area are summarised in table 1.



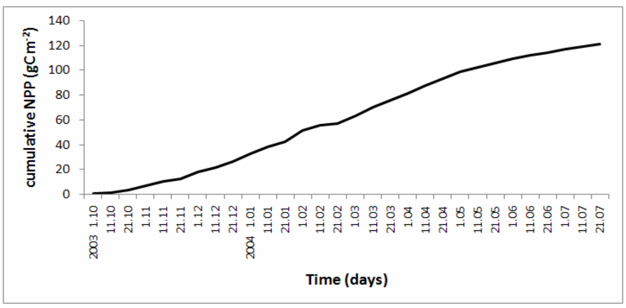


Figure 3a,b. NPP for the detected area 800. a) Time Series of the NPP (gC m^{-2}) for the 2003-2004 growing season. b) Cumulative NPP (gC m^{-2}) for the 2003-2004 growing season.

4.3 Combusted biomass calculation

The 2004 SEVIRI FRP database was imported in a GIS and it was clipped on the boundaries of the studied area. Following, the digitized polygons of the detected burned areas were imported in the GIS, and the two layers were overlaid. Using logical queries on the FRP 2004 geo-database, the corresponding to polygons FRP 2004 entries, were extracted. The extracts were imported in a spreadsheet and for every component (1km x 1km pixels) of every detected event, they were integrated. By integrating all the corresponding FRP entries of a detected burned area, one can examine the temporal evolution of the fire in 15 min resolution and estimate the FRE which, according to Wooster et al. (2004; 2005), is directly related to the amount of biomass that was combusted (equation 2) . The temporal evolution of one fire (area code 800) is given in figure 4. The combusted biomass of all the detected areas are listed in table 1.

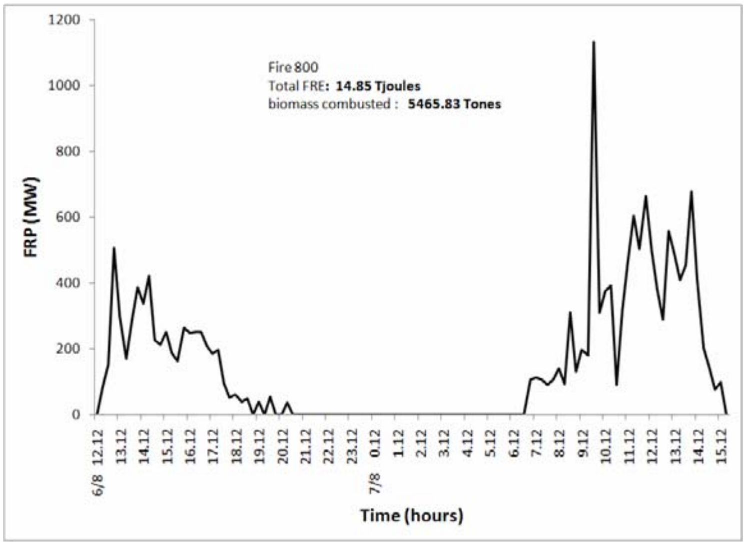


Figure 4. FRP time of a processed fires.Temporal evolution of the fire that burned the area 800 between the 6th and 7th August 2004.

5. Results

5.1 Fire and productivity characteristics

From the 18 fires that were processed, none of them were found to be active during night hours (between 2000 – 0500 UTC). The temporal evolution of all the fires resemble the FRP time series shown in figure 4 with the highest values occurring during morning and noon (0900 till 1400 UTC) and no values during the night. The implication of this is that during the night, the radiative power of the fire pixels drops below a radiation threshold that SEVIRI cannot record. There isn't any proof that the fires cease during night and re-ignite in the morning. The same observation was made from Roberts et al. (2005), who noticed that fires in Southern Africa savanna have a distinct diurnal behaviour with little or no activity over night and peak values between 1100 and 1400 (UTC). For all the 18 processed fires, we conclude that as a minimum estimate, the average combustion rates ranged from 200 to 400 kg sec^{-1}. The FRE ranged from 0.04 to 23.2 Tjoules combusting 15.5 and 8531.3 tones of biomass respectively. All the 18 fires combusted a total of 38,240 tones in a burned area of 270.06 km^2. Given the fact that atmospheric absorption of the upwelling radiation wasn't taken into account and the unavoidable underestimation of weakly burning fires from SEVIRI, then these results maybe increased upwards by a significant factor. The carbon productivity in the areas of study for 2003-2004 growing season ranged from 62 to 142 g C m^2 with an average of 104 g C m^2, while the biomass productivity from 129 to 297 g m^2 with an average of 220 g m^2. We used the fuel load product from the Global Fire Emissions Database version 2 (van der Werf, 2006) to validate the SPOT derived NPP. Although the fuel load product has a poor resolution (1^o x1^o) comparing to the SPOT derived NPP (1km x 1km), the two products show, relatively, good agreement. For the areas of study, the GFED product estimates 129-141 g C m^{-2} for August while the SPOT derived NPP estimates an average of 104 g C m^{-2}.

5.2 Pre-burn available and combusted biomass comparison.

Our main objective was to examine the statistical relationship between the pre-burn available biomass derived from the SPOT VGT NPP product and the combusted biomass derived from the SEVIRI FRP product for a number of detected burned areas in southern Africa savannas (table 1). Firstly, a correlation analysis was performed. For the 18 detected areas (n=18), a strong positive linear correlation was found (r = 0.93) between the variables. The significance test for (r) at the 99.99% confidence level showed that we had to reject the null hypothesis that there is no significant correlation between the two variables (r=0) and accept the alternative. A regression analysis was performed to describe the relationship between the variables (figure 5).

Count	Burned area code	Available Biomass (Tones)	Combusted Biomass (Tones)	Proportion combusted (%)
1	500	8193.92	5703.20	69.60
2	600	4465.80	3337.59	74.74
3	700	3308.36	1982.02	59.91
4	800	7736.45	5465.83	70.65
5	900	1858.41	1477.63	79.51
6	1000	1445.20	884.70	61.22
7	1100	1289.14	1261.37	97.85
8	1200	3015.36	2626.15	87.09
9	1800	336.96	15.49	4.60
10	1900	1179.24	837.33	71.00
11	2000	3388.48	431.26	12.73
12	2100	2902.55	2145.26	73.91
13	2200	2822.31	1694.83	60.05
14	2300	2841.02	629.92	22.17
15	2400	1393.06	228.38	16.39
16	2500	7126.60	3852.52	54.10
17	2600	832.21	282.56	34.00
18	2900	6744.41	5384.15	79.80

Table 1. List of pre-burn available and combusted biomass for the 18 detected burned areas that were processed.

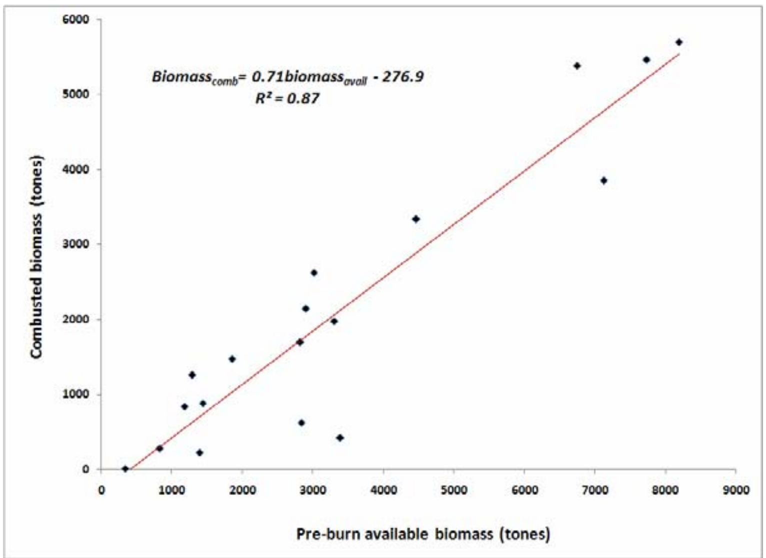


Figure 5. Combusted biomass (tones) is plotted against pre-burn available biomass (tones) for 18 processed areas. The regression trendline is fitted and its equation is presented in the upper part of the graph.

The coefficient of determination (r^2 = 0.87) shows that 87% of combusted biomass's variability can be explained from the amount of pre-burn available biomass. The linear model between the variables is given from the equation that describes the regression's trendline (3).

$$biomass_{comb} = 0.71 biomass_{avail} - 276.09 \tag{3}$$

From all the detected areas, 1800, 2000, 2300, 2400 (see table 1) don't fit the general trend and they can be thought as outliers. Outliers can only be removed from the analysis if there is a good understanding of "why" the particular points are outliers. In our case, this question takes the form: Why is the available biomass in these areas not combusted in the same average proportion (50-70%) as with the rest of the areas? The explanation should be sought in SEVIRI's characteristics and its ability to record the FRP of hot pixels accurately. Roberts et al. (2005), highlight SEVIRI's inability to detect and measure accurately small scale or weakly burning fires (less than ~ 100 MW) (Roberts et al., 2005). Given the fact that the average FRP of the fires that were processed is close to this threshold then a significant underestimation may have taken place. Furthermore, the amount of clouds covering the burning areas during SEVIRI's sampling times could be a potential source of underestimation. The latter was treated from the processing team (Roberts et al., 2005) by adjusting the FRP for cloud cover, but still an uncertainty remains.

Having a sufficient understanding of the nature of the outliers, we proceeded in omitting them from the analysis. By omitting them, the regression analysis we obtained had an even stronger relationship (r^2= 0.94) between the two variables (figure 6). The equation of best fit without the outliers becomes:

$$biomass_{comb} = 0.68 biomass_{avail} + 68.22 \tag{4}$$

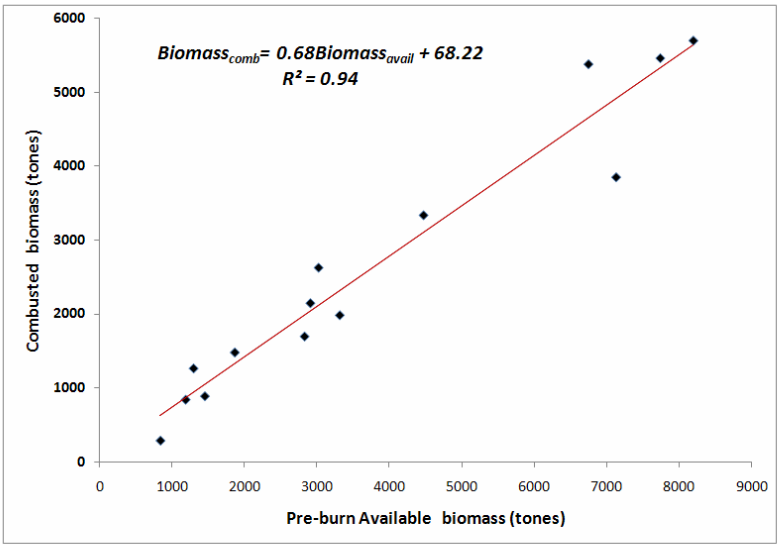


Figure 6. Combusted biomass (tones) is plotted against pre-burn available biomass (tones) for 14 processed areas excluding the outliers. The regression trendline is fitted and its equation is presented in the upper part of the graph.

5. Discussion

The results indicate that there is a linear and highly significant relationship between the pre-burn available biomass and the amount that is actually combusted from southern Africa savanna fires (r^2 = 0.94, n = 14, p < 0.001). Apart from its promising results, this study's importance lies in the fact that different products from different sensors were used successfully in order to answer the existing hypothesis.

There are several implications derived from this study. If one knows the size of the area that was burned, one can easily estimate the pre-burn available biomass (using the SPOT VGT NPP product) and use the proposed model (3) or (4) to estimate the amount of biomass that was combusted. Knowing the amount of biomass that was combusted, one can estimate the amount of carbon that was released in the atmosphere. Moreover, if one knows the amount of combusted biomass (e.g by using the FRP method or emission factors) one can estimate the amount of pre-burn available biomass and roughly the size of the area that was burned. This study was applied to burned areas in grassland savannas of southern Africa and there is no knowledge if it can be applied in other biomes.

The sample size of this study could, however, be a limitation. Although we came up with a very strong significant correlation ($r = 0.97$) and a good model ($r^2 = 0.94$), a bigger sample would increase our confidence in making any assumption. However, no matter the sample size, any value of r bigger than 0.7 or 0.8 should be taken as significantly important. Even with a sample size of $n = 15$, it would take an r value of 0.51 to reach significance.

The SPOT VGT NPP product was validated and compared with the GFED version 2 and several other relevant studies and good agreement was found in terms of carbon and biomass productivity in the areas of study. Most of the uncertainties in this work come from the combusted biomass estimates and the SEVIRI FRP database. The fact that SEVIRI underestimates fires outside the range of 665 – 1365 K (Roberts et al., 2005) leads to the assumption that the temporal evolution of some and especially small scale fires isn't accurately recorded. Especially at the beginning and towards the end of the fires' life, there are losses of recorded radiative power which lead to an underestimation of the fires' FRE and combusted biomass. However, given the small contribution of these fires to the total combusted biomass and trace gas emissions the loss isn't that significant (Roberts et al., 2005). It is certain that SEVIRI will produce the most accurate FRP observations for big and intense fires with FRPs in the range between 100 – 1000 MW (Wooster et al., 2005). The importance of the latter increases as many of the "hot" pixels processed in this study were radiating less than 100 MW. This has two implications. Firstly, there is big probability that the calculated FRE is an underestimation of the true FRE. Secondly, the fires in the areas of study weren't that intense despite the fact that they are burning in the late dry-season. This is probably due to the low productivity of these areas (150 - 300 g biomass m^{-2} $year^{-1}$). It is certain that we may have had more accurate results if the processed fires were more intense and their temporal behaviour was fully and more accurately observed. Another source of potential FRE underestimation is cloud cover. Due to this, the 2004 FRP database includes cloud corrected observations. We have no direct knowledge on the treatment of cloud cover in the SPOT VGT NPP estimation and especially on the (fAPAR) estimation which is the fraction of absorbed PAR (photosynthetic active radiation) calculated from the VGT S-10 NDVI. Another uncertainty comes from the fact that we can't be accurate enough about the exact period when the biomass started accumulating in the areas of study. In this work we assumed that all the areas which burned in the late dry season had started to accumulate biomass from the beginning of the preceding growing season (01/10). The amount of biomass that wasn't combusted in the 2002-2003 fires is another factor of pre-burn available biomass underestimation. Ideally, this amount should be added to the available biomass derived from the SPOT VGT NPP. However, as Korontzi (2005) points out, this amount must be small, given that the efficiency of fires in savannas increases as the biomass becomes drier towards the end of the dry season reaching almost 98%, and combusting almost all of the dry fuel that is available at that time. Moreover, there is no direct knowledge of the amount of biomass that is consumed through grazing during the period preceding the fires. Given the fact that these areas are extensively used for grazing, the latter could be an important factor in pre-burn available biomass over-estimation. Burned area detection and mapping is a straight forward process especially for late dry season savanna fires. The altered spectral characteristics of the areas right after they are burned (1-5 days) are easily identifiable (figure 2) and thus easily measured. The spatial resolution of MODIS bands 1 and 2 (250m) allows for relatively accurate burned area mapping and together with the frequent overpass, MODIS sensors are proven to be the most appropriate for any similar work.

Any future work on the same subject should use a bigger sample of burned areas so as to increase the significance of any proposed model. Moreover, application of the proposed methodology in other continent savannas would be a good way to validate our results and increase the models applicability. Knowledge of the consumed biomass through grazing is another factor that could be studied in order to increase our confidence in the proposed model. The SEVIRI FRP data could be validated by using near-coincidence MODIS FRP data. Knowing that SEVIRI typically underestimates small/ weakly emitting fires when compared with MODIS (Roberts et al., 2005) we expect for the detected fires SEVIRI FRP to be smaller than MODIS FRP.

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