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Strengths and weaknesses of MODIS hotspots to characterize global fire occurrence

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ABSTRACT

MODIS fire hotspots have been widely used to study fire occurrence at a global scale as they provide highly relevant information on fire events, on their spatial and seasonal trends. Nevertheless, they present some difficulties to estimate the actual magnitude of fire activity, as the relations between active fires and burned areas are not constant in space and time. Some previous studies have demonstrated that the total burned area can be estimated from the number of hotspots using regional models, but relations were established with coarse resolution data. We present in this paper a more detailed study on the relations between MODIS hotspots and burned areas, as extracted from Landsat images, which are commonly considered as reference data for validation of global burned area products. The comparison has been conducted in nine study regions with significant fire activity and in a sample of sites with low fire occurrence. Our results show that MODIS hotspots are very reliable to detect true burned areas, with only 1.8% of them not associated to actual burned patches, except for urban areas where very high commission errors were observed. On the contrary, the number of burned patches not detected by MODIS hotspots was found relatively high considering all fires (36–86%), decreasing for burn patches with a larger size (0–20% for burned patches larger than 500 ha) and for areas with a lower grassland and shrubland cover. A linear relationship between the number of hotspots and the total burned area was observed within each study area. However, the slope of the regression varied strongly between study sites. It was observed that sites with a larger proportion of grass and shrub cover had a larger mean burned area associated to each hotspot. The results presented in this study improve the understanding of the spatial variability and characteristics of the hotspots and should help to use the hotspots in future research.

1. Introduction

Forest fires are an important environmental factor at global scale, influencing vegetation dynamics (Bond et al., 2005; Van Langevelde et al., 2003), carbon stocks (Bond-Lamberty et al., 2007), land use change (Bowman et al., 2009) and being an important emission source of greenhouse gases and aerosols (van der Werf et al., 2010). However, large uncertainty exists on the distribution, extent and intensity of fire occurrence at global scale and the resulting biomass burned (FAO, 2010; Giglio et al., 2010; Tansey, Gregoire, et al., 2008). Satellite products are the only source of global information on fire occurrence, since they provide a comprehensive spatial and temporal coverage of fire affected areas. Two types of satellite data products have been used for mapping fire occurrence: hotspots (HS) and burned area patches (BA). HS are derived from temperature anomalies registered by the middle and thermal infrared sensors, while BA patches are detected by the reflective contrast between unburned and recently burned areas (mostly associated to the presence of char, ashes, and scorched leaves). However, HS only detect fires at the time of satellite overpass, which implies that hotspots are actually a sample of the total fire occurrence (Giglio, 2010), while reflectance changes of burned patches remain longer (from several weeks to years, depending on the ecosystem response to fire). Additionally, when fire events occur under dense cloud cover, they may not be detected, thus creating additional fire omissions (Schroeder et al., 2008).

Various satellite sensors have been used to extract HS: AVHRR (Dwyer et al., 1998; Fuller & Fulk, 2001; Nielsen et al., 2002), ATSR (Arino et al., 2007), TRMM VIRS (Giglio et al., 2003), MODIS (Giglio, 2010; Giglio et al., 2006) and the geostationary satellites GOES (Prins et al., 1998) and MSG (Amraoui et al., 2010; Calle et al., 2006). The AVHRR sensors were used to produce the first global fire occurrence datasets (Dwyer et al., 1998), although with certain limitations because its middle-infrared channel was not well suited for this purpose. The design of the MODIS sensor took into account these experiences, by greatly improving the number and sensitivity of thermal channels, being nowadays the most widely used sensor for active fire detection. HS data have been used in a broad range of fire related applications such as the estimation of gas emissions from fires (van der Werf et al., 2003, 2004, 2006) and the analysis of fire regimes (Chuvieco et al., 2008; Harrison et al., 2010). Furthermore, fire radiative power can be estimated from these thermal

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anomalies, giving additional information to estimate the amount of biomass burning, combustion ratios and emissions of aerosols and gases (Kumar et al., 2011; Roberts et al., 2005; Vermote et al., 2009), although practically this is only possible from the MODIS sensor and beyond.

HS have also been used to estimate total BA (Giglio et al., 2006, 2010; van der Werf et al., 2003), particularly as an input to the emission databases (GFED: http://www.globalfiredata.org/). These studies are based on the assumption that an HS is always associated to an actual fire and that it covers a certain burned area. Both relations need to be quantified, as they vary for different ecosystems (Giglio et al., 2006).

Even though HS have been used as a surrogate of fire activity for a wide variety of studies, few of them have studied the relations between HS and BA. Most existing HS datasets have been validated by comparing them with other thermal anomaly detections at higher resolution: MODIS HS have been validated with ASTER and Landsat ETM+ data (Csiszar et al., 2006; Morisette et al., 2005; Schroeder et al., 2008), (A)ATSR HS have been compared to MODIS HS and TRMM-VIRS (Arino et al., 2012), GOES HS have been validated by Aster and Landsat ETM+ (Schroeder et al., 2008) and MSG-SEVIRI HS with MODIS and AWIFS data (Calle et al., 2008). Characterizing the relation between HS and BA is essential to better understand what actual information on fire activity is included in HS databases. At global scale, Giglio et al. (2006) compared MODIS BA and HS to derive regional estimation models of BA. This study compared two products from the same sensor, and with similar spatial resolution, and therefore the estimations were affected by the BA product errors. Additional studies have been published on comparing HS and BA for particular areas. For instance, Smith et al. (2007) working on agricultural stubbling burning noticed that only 13% of the fires were detected by HS. Tansey et al. (2008), analyzing fire occurrence in Borneo from Landsat imagery, found that 60% of fire perimeters were omitted by HS and 8% of HS were not associated to burned patches. The average BA HS^{-1} was 15–16 ha. Hawbaker et al. (2008) used 361 fire (>18 ha) extracted from Landsat imagery to determine the relation and errors of MODIS HS in the United States. They observed omission errors of 18%, mainly related to the size of the burn patch. At a global level, relations between HS and BA have not been carried out with Landsat-TM/ETM data, and therefore the relations between HS and the actual magnitude of fire occurrence remain uncertain.

The main objective of this study was to quantify the relations between MODIS HS and BA for different ecosystems particularly affected by fire activity, in order to better characterize fire occurrence at global scales from the available HS products. For doing so, we generated BA reference maps from Landsat imagery in relevant study sites to cover a wide range of global fire activity. Using this dataset we quantified: 1) the ratio of HS that are actually fires (that have burned areas associated), 2) the ratio of burned areas that are actually detected by HS, and the impact of fire size on detection rate, 3) the land cover influence on the detection and error rate, 4) the amount of area burned in each HS considering different ecosystems and land covers. Even though some of these questions have been previously addressed, published studies have never been based on fire perimeters derived from Landsat imagery, which is commonly considered the reference source for validating global BA products (Boschetti et al., 2009; Roy & Boschetti, 2009; Tansey, Gregoire, et al., 2008).

2. Material and methods

2.1. Burned area reference data

BA maps were produced covering 9 different study sites with an important fire activity, distributed over the globe (Fig. 1). These areas were selected to include representative regions with significant fire activity, covering different fire ecology conditions. Burned area estimates, carbon emissions and biomes were taken into account to select these study sites. They cover the major vegetation types with important fire activity, including Boreal, Temperate, Mediterranean and Tropical forest, as well as Temperate and Tropical grassland areas (Tables 1 and 2). Multiple scenes covering different years were processed for each study site in order to have enough data to obtain consistent results. Furthermore, nine additional Landsat scenes from low fire activity regions were selected to check the performance of HS in relation to false fire detections (Fig. 1).

The reference BA files were generated from multi-temporal analysis of two Landsat images. These BA maps were generated for each study site at a yearly basis (when imagery was available). The time span between the two Landsat images is variable, ranging from 16 days till almost the complete year, depending on image availability and ecosystem (in Boreal regions the burned signal last much longer than in Tropical regions). BA patches were labeled for the period between the two satellite acquisitions. Non-burned (including unburned islands) and non-observed areas (clouds, no-data, etc.) were identified and labeled as well.

The identification of burned perimeters was performed using dedicated software (ABAMS), which implements an automatic BA detection algorithm widely tested for temperate fires (Bastarrika et al., 2011). This algorithm first detects BA pixels that show a high confidence to be truly burned, and then improve the delimitation of fire perimeters using a contextual region growing criterion. Once the BA map was produced, it was visually verified by an independent expert interpreter. Wherever necessary, errors were manually corrected. More detail on the BA generation protocol can be found in Padilla et al. (2011). The minimum mapping unit of the BA patches was 1 ha. Input images were mostly acquired by the TM sensor from Landsat-5, but ETM+ images from Landsat-7 were also used from acquisitions prior to 2003, when the SLC-off data anomalies were observed. Exceptions were areas in Russia, Colombia and South Africa where very few Landsat-5 acquisitions were available and a manual interpretation and completion was possible to produce full BA perimeters for the central part of the scene. A total of 70 images were processed for this study. This high resolution BA database was produced under the framework of the Fire_cci project (http://www.esa-fire-cci.org/).

2.2. MODIS HS active fire data

MODIS temperature anomaly data, MCD14ML collection 5, of both Aqua and Terra satellites was downloaded from FIRMS (http://firefly.geog.umd.edu/download/). The time series covers from 2001 to 2009, but before 2002 only Terra HS were available, with an important data gap in June 2001. Therefore HS from 2001 were just used in the analysis of commission errors, that is those HS not associated to any BA patch. The HS data are in shape format where the point represents the center of the MODIS pixel, being 1 km at nadir (Giglio, 2010). The HS data acquired from MODIS sensor from the Terra and Aqua satellites are available from November 2000 and 4 July 2002 respectively. Terra passes the equator around 10:30 h and 22:30 h and Aqua around 13:30 h and 1:30 h and therefore there are generally 4 overpasses a day, with small data gaps at low latitudes (±30°) and more overlap with increasing latitude on both hemispheres.

The MODIS HS were extracted for the same temporal and spatial extent of the BA reference maps. In order to avoid identifying as omission BA patches located nearby the border of the Landsat frames, HS located within a 500 m buffer from the border were selected as well. Consequently, HS located just outside the scene were still associated to the border burn patches. HS were grouped based on their confidence value (0–100%): low confidence <30%, medium confidence 30–80% and high confidence >80% following the recommendations of Giglio (2010).

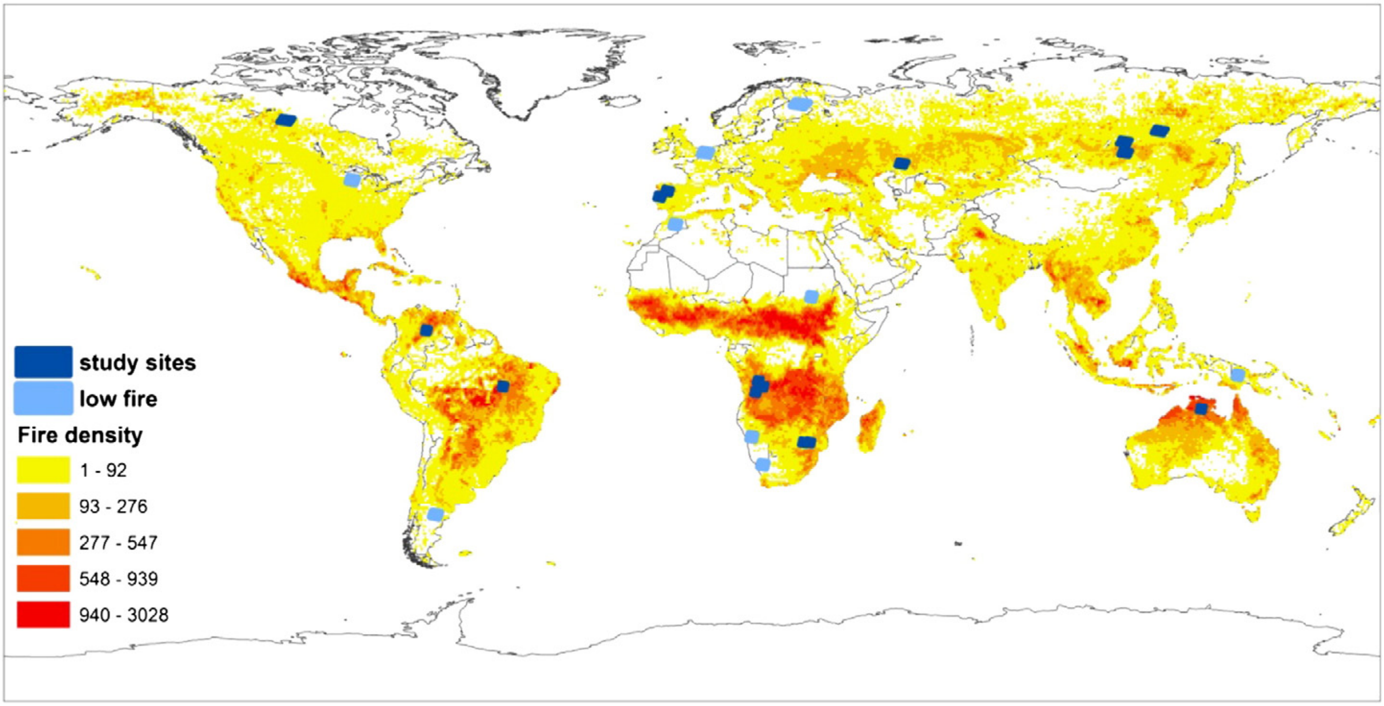

Fig. 1. The distribution over the world of the Landsat scenes used in this study, with the average number *10,000 of MODIS-Terra HS (nr./km^2/month) as a background.

2.3. Data analysis

A HS was considered associated with a fire perimeter when the HS was closer than 1500 m from the border of the BA patch. This choice considers all HS whose footprint at least partially overlaps the BA patch, as the fires can be anywhere within the MODIS thermal channel footprint (1000 m). In addition, this distance was selected to mitigate the impact of the change in pixel size under increasing observation angles, as well as impacts of minor registration problems ($\pm$1 pixel). In fact, around 10% of HS associated to BA patches were found within this external buffer (Fig. 2, Table 3).

We quantified three characteristics of the HS: 1) HS that were not related to BA patches (false positive or commission errors), 2) BA patches that were not detected by any HS (false negatives or omission errors) and 3) the relationship between BA and the number of HS. In all cases, the aim was to better understand what information on BA is actually included in the HS datasets.

As for commission errors, our hypothesis was that they should be generally low following published validation exercises, but they would have a higher ratio in those areas with bare soils, agricultural or urban areas. Commission errors should also be larger for lower confidence HS.

Concerning the proportion of undetected BA patches (omission errors) our hypotheses was that they should decrease when BA patch size increase, as smaller fires are more difficult to detect. On the other

Table 1
Description of the data used with the scene path/row, the number of different BA map of a scene used and the name of the study site with its corresponding vegetation type. With Mediterranean vegetation we want to indicate the mosaic of agricultural lands, grasslands and sclerophylous shrubs and forests.

Study site	Scene	Nr. of years	Years	Vegetation type
Canada	040/018	9	2001–2009	Boreal forest
Brazil	223/066	9	2001–2009	tropical savannas
Portugal	203/031	3	2001,2002,2009	Mediterranean
	204/032	3	2001,2003,2007	Mediterranean
South Africa	169/076	1	2001	Forest and shrub
	170/076	5	2002,2005, 2007–2009	Agriculture and shrub
Colombia	005/056	5	2001–2003,2006,2007	Grassland
Angola	180/067	2	2003,2008	Open woodland
	179/066	1	2010	Open woodland
	180/065	2	2001,2002	Open woodland
Australia	104/070	9	2001–2009	Tropical savannas
Kazakhstan	165/026	7	2001,2002, 2005–2009	Grassland
Russia	128/024	1	2008	Boreal forest
	129/022	3	2006,2007,2009	Boreal forest
	124/020	1	2008	Boreal forest
Low fire occurrence	024_029	1	2008	Forest and agriculture
	174_050	1	2008	Grassland
	099_064	1	2008	Rainforest and agriculture
	176_080	1	2008	Grassland
	179_074	1	2008	Grassland
	199_024	1	2011	Agriculture
	229_089	1	2009	Grassland
	200_037	1	2010	Grassland
	188/015	1	2008	Mixed boreal forest

Table 2
Overview of the fire information used for each study site, presenting the number of BA maps used, the number of fires, total burned area and number of HS as well as the percentage of the HS detected by the Terra satellite for each study site.

	# of years/ scenes	# of burned patches	Burned area (ha)	# of HS	% HS Terra/ Aqua
Canada	9	244	323,551	4550	53.8
Brazil	9	12,337	855,042	5737	45.4
Portugal	6	2207	239,844	2967	47.9
South Africa	6	2200	125,263	209	20.6
Colombia	5	7381	1,258,476	2432	52.4
Angola	5	26,205	2,317,447	10,270	24.3
Australia	9	2447	812,292	2269	39.5
Kazakhstan	7	647	1,292,215	2784	58.6
Russia	5	495	125,268	1794	53.6
Low fire	9	370	12,527	162	51.8

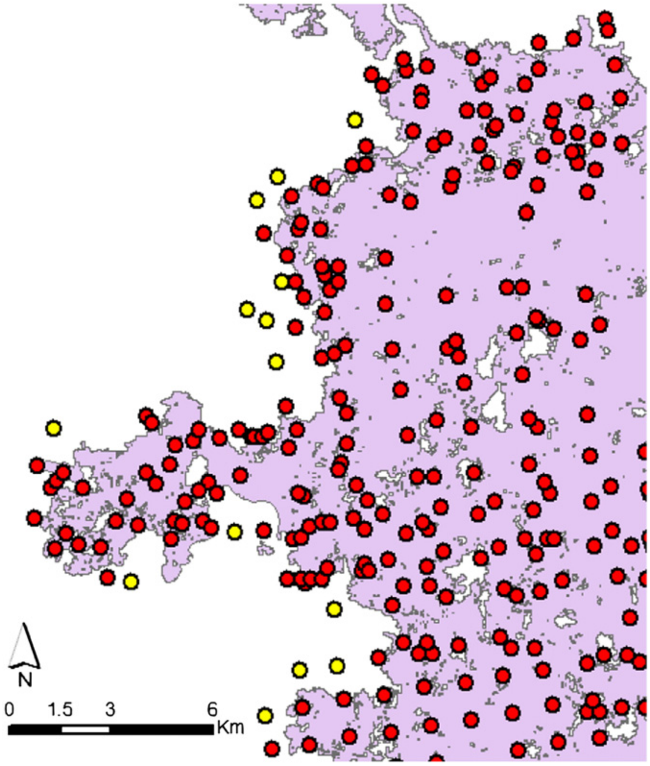

Fig. 2. Example of spatial relations between HS and burn patches for a fire in Portugal 2003. Red dots are HS<500 m and yellow dots are HS at 500–1500 m distance from the burned perimeter.

hand, we foresaw that the agricultural and grassland fires should have larger omission errors, as they burn with lower intensity than shrub or trees and during a shorter period of time.

Finally the relation between the number of HS and the total BA was derived from linear regression analysis. Our hypotheses in this case was that the relationships would be determined by land cover types, with the slope value depending on the amount of biomass available to burn, with lower values (less BA HS^{-1}) for forested areas and higher values (more BA per HS) for pasture and agricultural areas, due to the difference in duration and intensity of the fires (Giglio et al., 2006; Roy et al., 2008).

To avoid the impact of the large variability in fire activity between years the relations between HS and BA patches were computed for all years in each study site. The mean value of commission, omission and regression analysis was used for further analysis.

Table 3
The number of HS at determined distance from the fire perimeters, with HS situated at more than 1500 m, being HS that cannot be related with any fire perimeter and considered commission errors.

	Number of HS			Commission error (%)			
					Confidence		
Dist. to BA	<500 m	500–1500	>1500	Total	<30	30–80	>80
Canada	4145	351	54	1.19	3.24	1.54	0.15
Brazil	4965	553	219	3.82	5.36	4.95	2.06
Portugal	2503	395	69	2.33	2.83	4.86	0.92
South Africa	179	22	8	3.83	0.00	4.90	1.61
Colombia	2279	137	19	0.78	1.48	1.15	0.00
Angola	9606	650	32	0.31	0.73	0.26	0.39
Australia	2187	66	16	0.71	0.00	0.95	0.37
Kazakhstan	2674	92	18	0.65	1.68	1.08	0.30
Russia	3734	193	45	1.15	2.56	2.11	0.23
Low fire	21	8	135	85.4	57.1	73.5	64.0

The GLC2000 dataset (European Commission, 2003) was used to extract the land cover information for every Landsat scene. When different Landsat scenes were used in one study site, we computed the land cover as a weighted mean of the land cover present in each scene, depending on the number of years each scene was used.

3. Results

An overview of the available data for each study site is presented in Table 2. For each study site a large number of BA patches as well as BA were detected, although with large differences between them. Obviously, the Low fire incidence group had the lowest number of patches, as well as total BA and HS. This dataset will be mainly used to improve the characterization of false positives or commission errors. As for the BA patch size distribution concerns, the Kazakhstan and Canada sites showed the largest values, while the smallest patches were found in the South African and Brazil sites. This large variety in patch size distribution roughly indicates a wide diversity of fire conditions between the different sites.

Most of the HS were associated to BA patches, with very small proportion of commission errors as presented in Table 3. Most of the HS are inside the BA patch (<500 m from the fire perimeter), although a significant proportion were found in the 1500 m buffer established around the fire perimeter (between 3.3 and 13.3% in the different sites). The ratio of HS not associated to any BA patch (>1500 m away from the fire perimeters) were most commonly lower than 1.2%, with the exception of Brazil, Portugal and South Africa showing false positive ratios of 2.3 to 3.8% (Table 3). The Low fire activity group showed very high commission errors, mostly related to urban and agricultural areas (Table 4). Commission errors were generally related to the HS confidence level, with higher commission errors for HS with a lower confidence level. Nevertheless, in the case of low fire activity areas, this trend was not evident (Table 3). For the other sites, only the higher confidence class (>80) had significant lower commission errors than the other two confidence classes (student *t*-test, $t=2.34$, $p<0.05$).

The observed commission errors were related to the land cover characteristics of the different study sites. Although urban and industrial areas had a minor cover in the study areas, they included 2.5% of false detections (Table 4). This was particularly clear in the Low fire activity group, as it includes two urban and industrial areas (NW-Europe and NE-America), which accounted for almost all commission errors observed in the low fire occurrence areas. To better quantify the relation between land cover and commission errors we performed a regression analysis for the nine study sites between commission error and land cover type. A high correlation coefficient ($R^2=0.77$) between the commission errors and the fraction of agricultural land cover was found (Fig. 3), while the other land cover types did not present any significant trend.

The omission errors of the HS were determined by the number of BA patches that did not have a single HS associated (nearer than 1500 m). The ratio of omitted BA patches was higher than 35% for all sites, with values reaching 86% in the case of South Africa (Table 5).

Table 4
Number of hotspots considered commission errors per vegetation type, the average weighted % vegetation and the number of hotspots per % weighted landcover.

Vegetation type	# of hotspots commission	%HS commission (A)	% weighted landcover (B)	A/B
Forest	272	45.2	36.59	1.23
Shrub	49	8.1	14.71	0.55
Pasture	113	18.8	27.08	0.69
Agriculture	147	24.4	11.10	2.20
Water/snow	6	1.0	10.38	0.10
Urban	15	2.5	0.14	17.70

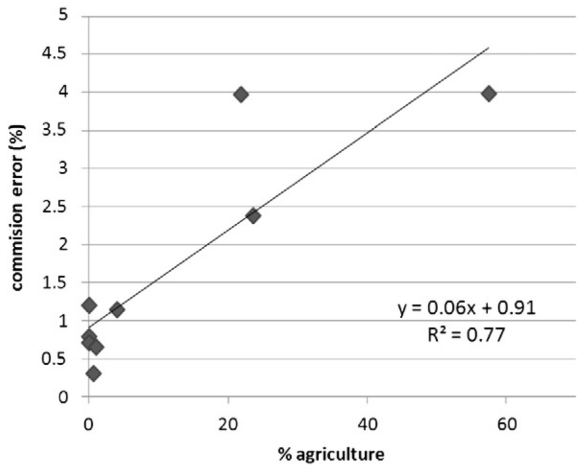

Fig. 3. Relation between commission errors and % of agricultural land cover in the study sites, considering each study site as a sample.

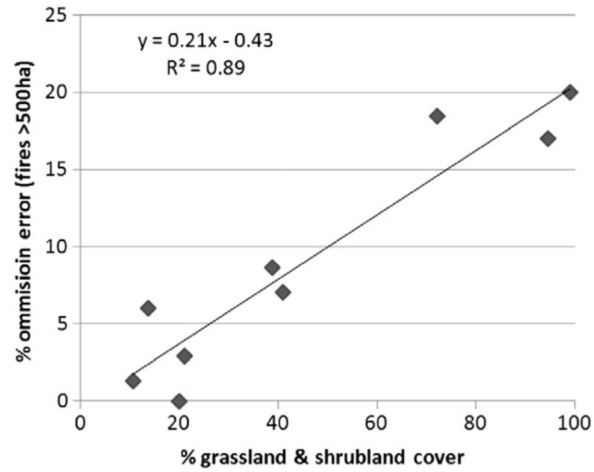

Fig. 4. Correlation between grassland and shrubland cover (%) and omission errors, considering each study site as a sample.

The ratio of undetected patches varied greatly with the size of the burned patch. For small fires (<50 ha) the ratio detected was quite low (10–50%), while the larger patches (>500 ha) were generally well detected (>80%). However, relevant differences were found between study sites, with Colombia, Kazakhstan and Australia presenting relative high omission errors (>15% for fires >500 ha). These omission errors were related to the grassland and shrubland cover of the study sites, with higher omission errors for areas with more extended grassland and shrubland covers (Fig. 4). The percentage of BA omitted for the different study sites was highly variable. The Boreal sites showed very low BA omitted (<3%), while for the Tropical savannas the proportion is more significant, with 28% in Brazil and 44% in South Africa.

The BA could be estimated from the number of hotspots using a linear regression analysis for each study site separately (Table 6 and Fig. 5). The regression coefficients for the relation between the number of HS and the BA (ha) strongly differed between study sites, with the slope of the regression analysis ranging from 65.7 to 439 for Canada and Kazakhstan respectively (Table 6). These differences were again related to the land covers (Fig. 6), where the slope of the regression analysis is well correlated to the forest cover ($R^2 = 0.61$) and the grassland + shrubland cover ($R^2 = 0.80$).

Dividing the BA by the number of HS we can obtain the BA related to each HS for the different study sites. The BA/HS has a broad range, starting at 68 ha/HS for the Canada site till 389 ha/HS for the Kazakhstan study site.

4. Discussion

The main objective of this paper was to characterize the BA information included in the MODIS HS datasets, by relating them to high reliable BA patches in different ecosystems. We found that HS are closely associated to true burned areas, with very low commission errors, particularly in natural areas with medium to high fire activity. High commission errors were found in areas of low fire activity, particularly in urban and agricultural sites. Most of the errors found in urban areas were in fact associated to industrial heat sources, but they should obviously not be associated to fire activity. This problem may be mitigated by using a precise urban mask to remove those HS. For non-urban areas, our results are in line with those of Tansey et al. (2008) where commission errors of 8% were observed for an area of degraded swamps in southern Borneo. It was observed that commission errors were very low for all confidence classes, although they were higher for lower confidence values. Therefore, we recommend using

Table 6
Regression coefficients for the relation between number of HS and BA for each study site, as well as the BA related to each HS.

	Slope	Offset	R^2	BA (ha)/HS
Canada	65.7	1434	0.99*	68
Brazil	104.9	25,047	0.95*	141
Portugal	83.8	−2863	0.99*	79
South Africa	127.2	1575	0.84*	192
Colombia	362.3	−16,896	0.99*	339
Angola	154.8	4161	0.99*	157
Australia	334.8	5776	0.73*	355
Kazakhstan	439.0	−17,503	0.95*	389
Russia	69.7	44	0.99*	70

* p<0.0.

Table 5
Number of burned patches/perimeters detected (D) and undetected (UD) by HS (<1500 m) for the different study sites and the omission errors (%) for the total of fire perimeters and the perimeters >500 ha.

	Number of fire perimeters								Omission error (%)		Omitted burned area (%)
	<50 h		50–100 ha		100–500 ha		>500 ha		All	>500 ha	All
	D	UD	D	UD	D	UD	D	UD			
Canada	57	62	15	10	31	7	42	4	36	8.7	2.8
Brazil	2259	7019	335	599	540	453	250	19	71	7.1	27.6
Portugal	286	532	41	33	82	21	31	2	57	6.1	7.4
South Africa	38	353	11	33	12	27	7	0	86	0.0	44.0
Colombia	221	1340	38	123	98	143	117	24	78	17.0	15.7
Angola	8808	9973	680	206	794	119	301	4	49	1.3	7.8
Australia	218	1435	44	143	124	186	137	31	77	18.5	11.2
Kazakhstan	54	159	7	19	22	27	48	12	62	20.0	5.8
Russia	188	189	28	7	43	6	33	1	41	2.9	1.7

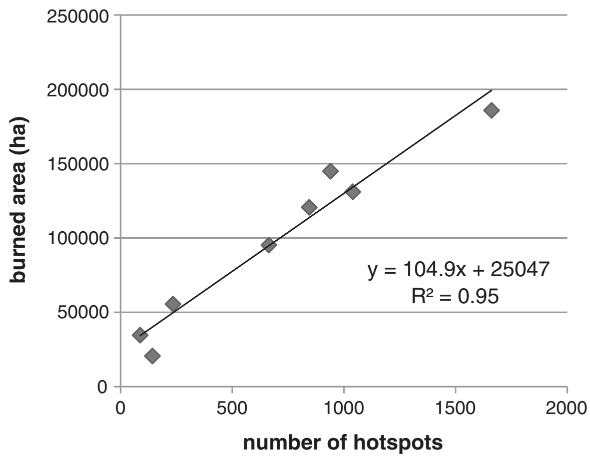

Fig. 5. Example of the regression analysis between number of HS and BA for the study site of Brazil, with each point representing the values of one year.

all available HS, as the additional information that low-confidence HS provide outweighs the potential problems related with their slightly higher commission errors.

Omission errors were generally high, with values reaching 86% for the South Africa site. This means that only 14% of the BA patches were in fact detected by HS, just representing 56% of the total BA in the study site. These values were in line with the observations of Smith et al. (2007) who reported a 13% detection rate for stubble burns in southern Australia, with both areas having an important agricultural/pasture cover. Tansey et al. (2008) observed omission errors of 60% in Southern Borneo, comparable to the 71% observed in the tropical study site of Brazil in our study. On the contrary, Hawbaker et al. (2008) observed omission errors of just 18% for the United States. However, these results may be strongly influenced by the fact that this study focused especially on very large fires. Although the omission errors found in our study are high, they are mainly due to a large amount of small fires (<50 ha) omitted. When considering only large fires (>500 ha) omission errors dropped significantly, but important differences were found for different land cover types, with higher omission errors for areas with higher grassland and shrubland covers. For areas with dense tree cover, omission errors were <10%, while for steppe vegetation in Kazakhstan we found errors close to 20%. Since most of the omitted burn patches are small in size, the total amount of undetected BA was generally low (detected patches account for >90% of total BA). The exceptions were those areas with many small fires or savannah/grassland ecosystems where omitted BA patches account for >40% of total BA.

Good linear relation between the number of HS and BA has been observed for each study site, in good agreement with previous studies (Giglio et al., 2006; Tansey et al., 2008). A wide range of BA per HS was observed between study sites, ranging from 68 ha HS^{-1} for the Canadian site to 389 ha HS^{-1} for Kazakhstan's. These values fit nicely between the extremes found by the global study of Giglio et al. (2006), ranging from 29 ha HS^{-1} for South America to 660 ha HS^{-1} for Central Asia. These values are much higher than values observed by Tansey et al. (2008) for South Borneo (15–16 ha HS^{-1}). This difference may be caused by a correction factor included in their study, which took into account only the proportion of fires detected by HS in their calculation of BA HS^{-1}.

The relation between the number of HS and BA was found to be dependent on the land cover. We observed good correlation between the slope of the regression of HS to BA ($R^2 = 0.61$ for forest cover and $R^2 = 0.80$ for pasture and shrubland cover). Forest cover has a negative correlation with the slope, while pasture and shrubland have a positive one, resulting in larger BA HS^{-1} ratios than those found in forested areas. These trends may be related to the duration of the fire and the energy released, which is directly linked to the available biomass to burn and the fire propagation conditions. These tendencies are in line with our hypothesis and have been observed by other authors (Giglio et al., 2006, 2010).

Although MODIS HS have been extensively used for a wide range of fire-related applications, our results indicate that they should be used with caution, keeping in mind external controlling factors, such as land cover and spatial variations in fire regimes. For instance, their use in fire regime analysis should take into account that omitted BA is clearly dependent on BA patch size and land cover, and therefore a bias towards large fires may be created.

We observed that HS describe very accurately fire occurrence in some ecosystems, while others are not well characterized. For instance, in Boreal forests, very low omission and commission errors were observed, and a high density of HS per BA was found. However, when many fires are not detected, and therefore the BA may be greatly underestimated, as is the case of South Africa site, the usefulness of HS for characterizing fire activity is very limited. de Klerk (2008) who studied the performance of MODIS HS for the following up of fire occurrence in the South African Fynbos biome reached a similar conclusion. She found that the use of MODIS HS to determine recurrence intervals was not feasible due to the high rate of omission errors. Similar problems may occur for regions with a very high BA HS^{-1} ratio. In these regions, particularly in grassland vegetation types, HS cover very small parts of burn patches.

HS have been used to estimate BA in two different ways. On one hand, by using regression models between the number of HS and BA (Giglio et al., 2006, 2010; van der Werf et al., 2003) and on the other

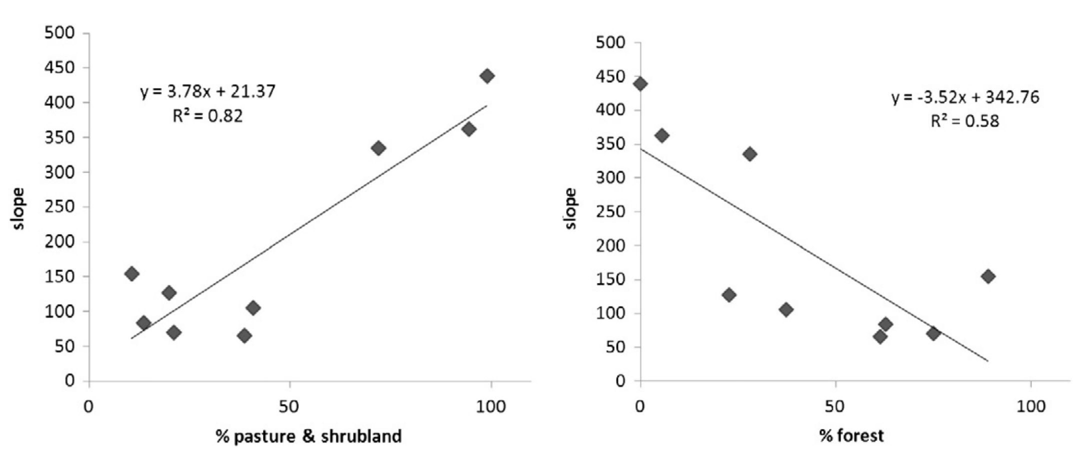

Fig. 6. Correlation between slope of the regression analysis between the number of HS and BA and land cover characteristics, where each point is the mean of a study sites.

hand as an input for mapping BA, using hybrid algorithms. In this case, HS are used to help identifying seed pixels or to sample true burned pixels to reduce commission errors (Fraser et al., 2000; Giglio et al., 2009; Roy et al., 1999). The first approach is very sensible to the vegetation type as indicated by our results, with very large differences in the relation between the BA associated to each hotspot. These differences should be established using high quality BA data to improve the estimations, particularly in areas with a large proportion of small fires. For the later, both commission and omission errors should be taken into account. Even though commission errors are generally very low, they may lead to errors in areas with low fire occurrence. Furthermore, areas very unlikely to be burned (urban covers) should be previously masked out. Omitted BA patches are relatively high, especially in the case of small patches, and therefore using HS in hybrid algorithms should be used cautiously, particularly for areas with large pasture and shrub land covers. For these areas, alternative BA detection methods should complement the detection based on HS.

5. Conclusions

In this study MODIS HS were compared to Landsat BA reference maps for the most relevant global biomes. Commission errors were generally low and mainly related to agricultural land cover. High commission errors occur in areas with large urban and industrial activity. Omission errors were mainly related to BA patch size, with very high omission errors in areas dominated by small patches. A large variability in mean BA associated to each HS was observed.

These results indicate that hotspot databases should be used cautiously. It is essential to take into account this variability when using HS for fire ecology and fire regime studies. When using metrics related to fire density of fire return interval, it should be very relevant to consider the spatial variability in BA HS^{-1} ratio and omission errors. Furthermore, it is doubtful if HS can give enough detailed information on fire occurrence in areas dominated by small fires. The results in this study indicate the complexity of using fire HS as an indicator of BA extent, even though it is a very relevant source of information for fire activity, particularly for seasonal and inter-annual variations.

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