Ten years of global burned area products from spaceborne remote sensing - A review:

Analysis of user needs and recommendations for future developments

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Abstract

Early global estimates of carbon emissions from biomass burning were based on empirical assumptions of fire return interval in different biomes in the 1980's. Since then, significant improvements of spaceborne remote sensing sensors have resulted in an increasing number of derived products characterising the detection of active fire or the subsequent burned area. When coupled with global land cover and vegetation models allowing for spatially explicit fuel biomass estimates, the use of these products help to yield important information about the spatial and the temporal variability of emission estimates. The availability of multi-year products (>10 years) leads to a better understanding of uncertainties in addition to increasing accuracy. We surveyed a wide range of users of global fire data products whilst also undertaking a review of the latest scientific literature. Two user groups were identified, the first being global climate and vegetation modellers and the second being regional land managers.. Based on this review, we present here the current needs covering the range of end-users. We identified the increasing use of BA products since the year 2000 with an increasing use of MODIS as a reference dataset. Scientific topics using these BA products have increased in diversity and area of application, from global fire emissions (for which BA products were initially developed) to regional studies with increasing use for ecosystem management planning. There is a significant need from the atmospheric science community for low spatial resolution (gridded, ½ degree cell) and long time series data characterised with supplementary information concerning the accuracy in timing of the fire and reductions of omission/commission errors. There is also a strong need for precisely characterising the perimeter and contour of the fire scar for better assimilation with land cover maps and fire intensity. Computer and earth observation facilities remain a significant gap between ideal accuracies and the realistic ones, which must be fully quantified and comprehensive for an actual use in global fire emissions or regional land management studies.

1 Introduction

As early as the 1980's, fire disturbance has been considered as an essential climate variable (ECV) (Crutzen et al. 1979, Crutzen and Andreae 1990, Hao and Liu 1994), and later by the Global Climate Observing System (GCOS 2010) program as well as by several other internationally coordinated science plans and research programmes. The main goal of current research is to move towards a better understanding of the earth system for more accurate predictions of various feedbacks in the future scenarios of climate change. It is now recognised that fire is one of the most important disturbances for terrestrial ecosystems causing considerable uncertainties in carbon balance, and in the atmospheric composition of reactive gases and aerosols (GCOS, 2011). In many regions of the world, the variability of the terrestrial carbon balance is driven by fire disturbance, including emissions during the burning itself, but also subsequent ecosystem recovery and regrowth, which may take place over long time scales (Mouillot and Field 2005, Field et al. 1999, Chen et al. 2000). Associated carbon fluxes, particles or aerosol emissions in the atmosphere then play a significant role on the global energy balance and subsequent climate trends. Therefore better fire observations and improved estimates of fire impacts will reduce uncertainty and improve prediction for future ecosystem feedbacks on biosphere/atmosphere interactions.

The research on global Burned Area (BA) remote sensing products started in the late 1980's with the technical work to deliver the global representation of fire number and burned area. Regional analysis of burned areas showed the potentials of middle resolution sensors to discriminate fire-affected areas (Chuvieco and Congalton 1988, Furyaev 1985, Milne 1986, Smith and Woodgate 1985). Later on, the first studies oriented towards continental burned area assessment were based on NOAA-AVHRR images, both at continental (Barbosa et al. 1999) and global scales in 2000 (Dwyer et al. 2000). Since the year 2000, several products have been delivered using different algorithms and sensors that we will describe in this paper. An unexpected side effects of these BA development has been the increasing use of these global data for regional fire regime analysis where fire statistics are lacking, and representing nowadays a significant community of users. In this context the European Space Agency's Climate Change Program aims to develop a set of ECV from satellite observations. Within this program the fire_cci project is developing methods to generate long-term and global series of BA products adapted to the needs of climate modellers for which global datasets started to be developed, but also land managers or local users when local fire

statistics are lacking. To make the final products more useful, the fire_cci project started from conducting a user requirement analysis, which was aimed to define the scientific profile of current end-users and their specific needs, covering all source of application, including climate modellers, earth scientists, ecologists and fire managers. The needs of BA information for each user group were defined in terms of coverage, accuracy, resolution, time delivery. This survey was complemented by a literature review, which analyzed the previous uses of BA datasets in the widest range of topics, but including the most representative of climate, carbon and atmospheric models. This paper provides a summary of current global BA data products and their uncertainties, limitations and applications, then presents the summary of the user-needs analysis, based on a survey of more than 47 questionnaires and finally includes a gap analysis for deriving a set of future needs and requirements that will be used to guide the production of global BA products in the next decades.

2 Overview of global burnt area data products

TABLE 1 HERE

Table 1 provides an overview of the global burned area products described in the literature from 1995 to 2010. The following sections will discuss the quality and accuracy of current global multi-annual data sets. For details on regionally or temporally restricted products the reader is referred to the literature cited in table 2. Even though the products described were developed with different sensors and algorithms, average yearly estimations of global burned area are fairly similar, in the range of 3.50 to 4.50 Mkm2, with yearly variations depending on weather conditions.

TABLE 2 HERE

2.1 GFED (Global Fire Emissions Database)

The Global Fire Emissions Database Version 3 (GFED3) includes estimations of atmospheric emissions derived from a multi-sensor global burned area data set derived by Giglio et al. (2010). These data are provided as gridded product at 0.5° resolution and cover the period from 1997 to present and thereby being the longest global burned area record currently available (Giglio et al. 2010). The multi sensor and bias-corrected burned area product has been improved compared with its predecessor GFED2 (Giglio et al. 2006), by using 18 times the quantity of training data for the algorithm implementation. Most input data for the GFED3 was obtained from BA maps generated

from the 500 m reflectance channels of MODIS using the direct broadcast (DB) algorithm described by Giglio et al. (2009). This algorithm uses both multitemporal reflectance changes and hotspots derived from the thermal channels. For periods when MODIS BA information was not available, the BA was estimated from a combination of local regression and regional regression trees from active fire data. For the Pre-MODIS era, active fire observations from the TRMM VIRS and ERS ATSR sensors were used, followed by a further correction to ensure consistency with MODIS data. Estimations of yearly global BA from this product range from 330 and 431 Mha with great inter-annual variability.

2.2 MCD45A1

The MCD45A1 data is currently the standard MODIS BA product for Collection 5 Level 3. It uses daily data from both Terra and Aqua MODIS at 500 m spatial resolution. The data set is provided as monthly layers (with the date of BA detection) covering the full period of MODIS operations (2000-present). The MCD45A1 product was generated using an algorithm based on a bi-directional reflectance change detection approach (Roy et al. 2008).

2.3 L3JRC

L3JRC global burned area data (Tansey et al. 2008) has been generated for seven years (April 2000 to March 2007) at 1 km from SPOT VEGETATION data. The product was based on a cooperative project coordinated by the JRC (Joint Research Center, Italy), along with other European centres (University of Leicester, the Université Catholique de Louvain and the Instituto de Investigação Cientifica Tropical, Portugal). The product was generated by using a set of regional algorithms based on the previous experience of the GBA2000 product (Tansey et al., 2004).

2.4 GLOBCARBON

The Globcarbon BA product was developed as one of the four land products of the ESA Globcarbon initiative to provide targeted, long-term, suited land products that can be readily merged into earth system models (Plummer et al. 2006, Plummer et al. 2007). Global burned area data were generated at spatial resolution of 1km, 10km, 0.25° and 0.5° with monthly temporal resolution, covering the 1998 – 2007 period. The data were produced by applying two regional GBA2000 algorithms on the 1-km SPOT VEGETATION data, and the GLOBSCAR algorithms on ERS2–ATSR2 and ENVISAT

AATSR data. The product includes the estimation of different sensors-algorithms, as well as a combination of some of them by union and intersection.

2.5 GBS

The Global Burned Surfaces was generated by the European Commission – JRC – Institute for Environment and Sustainability – Global Vegetation Monitoring Unit. It was derived from daily NOAA-AVHRR images using the reduced resolution (8 km) data set. The series includes the period from 1982 to 1999, based on a multitemporal change detection algorithm, as described by Carmona-Moreno et al. (2005). The authors note that their product is likely to miss a large fraction of fire activity due to the coarse resolution of the imagery used. The value of this product lies therefore mainly in the analysis of seasonal trends.

2.6 GLOBSCAR and GBA2000

These two projects served as a benchmark to develop global BA algorithms. GLOBSCAR was developed by the European Space Agency (ESA) and uses daytime data from ATSR-2 instrument onboard the ERS-2 satellite, while GBA2000 is an initiative of the JRC and it was based on SPOT-VEGETATION data. Experiences from these two projects were later used for the Globcarbon and L3JRC projects.

3 General overview on the increasing use of BA products reported in the literature since 2000.

We investigated the use of global BA products based on a database search of peer-reviewed papers referenced in Web of Science, and filtered according to keywords concerning the names of at least one of the global fire products previously reviewed or their input sensors for local, regional or global applications, in whatever field of research. Our request identified 231 references for the 2000-2011 period, dealing with the developing, validation or use of global BA products used for global or regional studies (synthesis table and references in Annexe 2) and active fire counts. Figure 1 illustrates the yearly number of references over the decade 2000 - 2011 using BA products information or related products called “active fire counts” from MODIS or ATSR. Papers dealing with global BA products started in 2000, and their number grew up with 5 to 10 publications per year evenly distributed between products generated from MODIS, TRMM, ATSR before 2008. Since 2008, the number of publications per year using satellite BA products increased to more than 15 and the majority of

publications (65 %) relied on data from the MODIS instruments. At the same time, 25 scientific publications use active fire counts, mostly derived from MODIS sensor since 2008, while ATSR was mostly used before that year. It can be concluded that the quality of the MODIS products and their easy acquisition stimulated research related to the fire topic.

FIGURE 1 HERE

We classified the scientific publications using BA products into the following main topics covering different research fields: technical delivery of BA products with their updates (called Earth Observation EO), fire hazard early alarm and survey/penalize systems, BA accuracy analysis or improvement, ecosystems and land management, vegetation models using fire global fire risk assessment modules or fire spread at the regional level, and atmospheric sciences (carbon emissions and aerosols or particles during fire events). The contribution of each of these topics in the literature survey is presented in figure 2. Atmospheric chemistry applications remain the dominant application of BA products with 20% to 50% of the published studies in our sample. Research applications for fire hazard analysis and forest/ecosystem management actually started later in 2006 and cover now a significant end-user group, implying a wider range of requests than global studies alone.

FIGURE 2 HERE

The regional distribution of the published papers shows a significant share of global studies (figure 3). Tropical regions follow in importance, particularly in central Africa, the Amazon Basin and SE Asia. This inter-tropical region actually represents more than 60% of the burned area globally (Mouillot et al. 2005), but most countries in this region do not have operational fire observation systems, and therefore official fire statistics are not very reliable. Additionally, there is a double interest in air chemistry due to the large amount of carbon and aerosols released from these biomes, and a significant demand for forest management and protection from deforestation.

FIGURE 3 HERE

Since 2006, we can observe an increase in the number of research publications dealing with agricultural fires. These low energy fires were not detected in earlier versions of fire products and could not be considered. As of yet, no conclusive analysis has been performed to quantify the contribution of agricultural fires to, for example, the MODIS burned area products. For the purpose of estimating trace gas and aerosol

emissions from fires it can be assumed that some overlap exists with bottom-up inventories of agricultural burning that are based on economic statistics.

As a brief summary, the analysis of peer-reviewed research publications highlights the increasing use of MODIS-derived products compared to any other products and the importance of these datasets for the tropics where ground data are lacking. The origin of end-users reflects the increasing accessibility of the dataset to the global community and the increasing independence of these end users in downloading and using these data for local use. We also noticed the significant use of active fire counts rather than BA data, highlighting the interest in high resolution datasets and fire contours. From this analysis, we can expect different user requirements according to the field of application, the extent of the region to be explored, and the country of origin with different expectations and access to the datasets. This analysis also points out that any set of future requirements will be driven by the atmospheric community but will also become closer to the increasing demand for fire hazard and forest managers.

4 A literature review on BA product applications

The following section describes the main uses of BA products and tries to summarize their requirements in terms of temporal, spatial and thematic characteristics based on identified gaps and failures.

4.1 Fire hazard assessment for ecosystem management

Fire has both positive and negative effects on the ecosystems and society, but most commonly it is considered as a natural hazard, as it affects people's lives and properties and ecosystem services. For this reason, fires tend to be avoided and when countries have an active fire suppression policy, fire risk assessment systems are in operation. Accordingly, the identification of the main factors explaining fire ignition and propagation becomes a very relevant research topic. The validation of those fire risk systems requires having accurate fire statistics available. Both fire ignition points and burned areas are required (Ardakani et al. 2001, Chuvieco et al., 2010, Robbins et al. 2008). In savannah-type ecosystems for example, identifying climatic or human drivers as well as frequently burned areas requires a fairly good representation of fire contours (Devineau et al. 2010, Archibald 2009), to promote fire-free areas where fire sensitive species could be conserved. Accurate fire detection with low spatial shifts is then standard requested information for vulnerable areas (Wright et al. 2007, Ressel et al. 2009). Among these vulnerable areas, we could identify a special focus of interest for

deforested regions where fire is a major tool for forest clearing. In these regions, however, several authors could deplore some caveats in differentiating fires and other disturbances where reburning and understory fires occur (Van der Werf et al. 2009, LePage et al. 2008, Pereira 2003, Morton et al. 2011).

These results are of interest to fire risk modellers at larger scale who need a conceptual knowledge of processes to be implemented in global fire modules or fire spread/initiation models at global (Thonicke et al. 2010) or regional scale (Anderson et al. 2009). Mapping large fire events in continuous forested ecosystems could contribute to a better understanding of their propagation. Requirements here are an accurate timing of fire occurrence on a daily basis and a finer spatial resolution for more precise fire contours. On the other hand, long time series of fire affected areas are necessary for getting a clear picture of a fire regime with time return intervals much larger than the 10 years available until now, so that most studies, until now had to use a combination of products to get the more accurate and longest time series available (Lepage et al. 2008, Bartalev et al. 2007, Bartsch et al. 2009). Providing a single product covering the longest period available would be a major step forward for fire risk assessment users.

4.2 Early warning fire alert systems and survey

The growing impact of catastrophic fire seasons have brought the public interest of establishing near real time fire alert systems. Early warning and fast extinction of fires are the only chance to avoid major negative impacts of fires on society and ecosystems. These requirements have already been listed by Davies et al. (2009) for MODIS products, or have been pointed out in scientific papers (Schroeder et al. 2008). Some efforts have already started to provide this information through active fire detection rather than burnt area (Biswajeet and Hamid 2010, Zhang et al. 2008). Nevertheless, a major requirement on the improvement of BA product when considering lower spatial resolution getting closer to active counts, would be the timing of the fire signal delivery with low omission errors that could lead to missed alerts with significant consequences. Commission errors would lead to false alerts that are less damageable if they remain in a reasonable proportion.

The political use of fire detection for survey and penalisation for illegal fires recently emerged in Bolivia (Redo et al. 2011) or Indonesia (Harwell 2000). We could also identify the use of fire detection as a proxy for societal conflict in some regions and its application for early warning and rapid response efforts of interest to human rights, humanitarian and security communities, as already assessed for Darfur (Bromley

2010). This political use of fire information then brings an additional constraint on fire detection accuracy or at least a clear explanation of uncertainties to prevent any responsibilities in false alarms or inaccurate locations that could penalise local inhabitants.

4.3 Atmospheric chemistry

Since the early work by Radke et al. (1978), Crutzen et al. (1979) and Seiler and Crutzen (1980) the interest in biomass burning as major emission source for trace gases and aerosols has gradually increased to become an important focus point nowadays. The underlying data were traditionally derived from national forest fire assessments (FAO 2001). During the 1990's, continental scale or regional scale studies started to provide remotely sensed spatially explicit fire datasets (Barbosa et al. 1999, Eva and Lambin 1998a,b). At the end of the 1990's and the early 2000's, the first global fire products became available from global remote sensing, providing a spatially and seasonally explicit distribution of fires and the first studies with fire emissions in atmospheric chemistry models derived from remote sensing data appeared. The aim was to provide an accurate estimate of the interannual variability of combusted biomass and biomass burning emissions (Schultz 2002) and its seasonal variability (Generoso et al. 2003) in a spatially explicit manner at the global scale. Since then, it has become a *de-facto* standard in atmospheric chemistry models to prescribe trace gas emissions from large-scale vegetation burns. These are based on remote sensing data and an empirical conversion of area burned and average biomass amount per grid cell into carbon and other compounds released into the atmosphere.

Field experiments and laboratory burns of litter material from various ecosystems provided insight into the emission factors for many gases and aerosols (Andreae and Merlet 2001, Akagi et al. 2011). Due to uncertainties in the burned area provided, maximum and minimum values were delivered. The time period covered was not exceeding 10 years, and they were mainly used in areas where no fire statistics existed, as in the tropics. For regions where fire statistics are available, it has been possible to construct longer time series of fire emissions (Chen et al. 2000, Mouillot et al. 2006, Schultz et al. 2008, Mieville et al. 2010).

Fire emissions can be estimated from two approaches: bottom-up and top-down. The former tries to estimate the main factors contributing to emissions from biomass burning, while the latter tries to estimate the actual amount of gas released from the observation of a fire itself or from atmospheric concentrations of that gas. The bottom-

up approach has been the most extended, based on the Seiler and Crutzen (1980)'s model:

$$\mathbf{M_i = A \cdot AFL \cdot \beta \cdot EF_i}$$

Where **Mi** is the emission of compound **i** (g m^{-2}), A is the area burned (m^2), AFL is the available fuel load (g m^{-2}), β is the burning efficiency (i.e. fraction of AFL that is consumed in the fire and released into the atmosphere), and $\mathbf{EF_i}$ is the emission factor of compound **i** ($g_i \cdot g_{DM}^{-1}$, where DM means dry matter).

Global BA products provide A in the above equation, which can be coupled with spatially explicit estimates of AFL and EF based on vegetation modelling for biomass, litter and its water status. This approach is the basis for the Global Fire Emissions Database (GFED) (Van der Werf et al., 2010).

The alternative estimates of gas emissions are based on a combination of active fire counts and TOMS aerosol optical depth retrievals (Duncan et al., 2003), daily active fires from geostationary satellites (Reid et al., 2009) or – more recently – emissions estimates based on a multi-sensor fire radiative power retrieval (Kaiser et al., 2009).

4.4 Biogeochemical models

The estimation of biomass from before the fire has been sometimes approached from spatially explicit vegetation models that simulate carbon assimilation and respiration, estimating fuel biomass and soil litter loads, their water status and the subsequent dynamic and post-disturbance effects. Until the end of the 1990's, major efforts were focused on conceptualising models able to simulate the seasonal and inter-annual variations of these fluxes at the global level based on soil and plant functional parameters, and climate (precipitation, solar radiation and temperature). These models can be divided into dynamic vegetation models that simulate intrinsically species composition and the seasonal variation in the canopy layer where NPP occurs, and biogeochemical models that are forced by fixed land cover, fire and soils maps and by the fraction of photosynthetically active radiation (FAPAR) intercepted by leaves, globally estimated by remote sensing and reviewed in Palacios-Orueta et al. (2005). Biogeochemical models are then used for historical short term (over a decade) studies where changes in land cover are assumed to be not significant at a global scale. The CASA model was initially developed for estimating seasonal and inter-annual variability in biosphere/atmosphere exchanges (Potter et al. 1993, Field et al. 1995). The combustion module developed in CASA by Van der Werf et al. (2006) for GFED, and

Mouillot et al. (2006) for historical long term fire emissions, accounts for fire effects on changes in carbon stocks, direct emissions from combustion and subsequent indirect effects on the decomposition of woody debris resulting from incomplete combustion (Potter et al. 1998). Emissions ($\mathbf{M}_{BB}$) are calculated for the burning of leaves, wood, and litter carbon pools with specific combustion completeness parameters specific to these pools and to the biomes. Combustion completeness is then modified according to soil water content, the driest conditions being the more complete. Biome-BGC (Running et al., 1993) is also a widely used model for forest ecosystems, and has a range of global and regional application but has rarely been used in global fire studies (Wang et al., 2011). Fire-BGC (Keane et al., 1989), the stand level forest model designed for fire application is the mostly used BGC derived model implying fires but mostly at the landscape scale.

When applied at global scales, vegetation models require a spatially explicit representation of burned areas as a forced input for calculating combustion. Biogeochemical models require the accurate location and timing of fires for a better simulation of fire emission and combustion efficiency and further use in atmospheric models. We'll note here also the importance of multi-year datasets, as a single year for BA product is not relevant due to the high interannual variability and indirect effects of previously burnt areas on present fuel biomass. However model requirements in terms of BA specificity are still low compared to the current resolution of spaceborne sensors with global coverage, as simulations are performed at 0.5° or 1° resolution and on monthly basis.

4.5 Dynamic Global Vegetation Models (DGVMs)

DGVMs simulate water, energy and carbon exchanges between the terrestrial biosphere and the atmosphere, but instead of using a fixed land cover derived from global remote sensing, they can simulate the global distribution of vegetation dynamically so that land cover (species composition and biomass) is calculated from climate and soil types that allow the germination, growth and survival of species (Sitch et al., 2003). Indeed they can be used under historical and future climate change scenarios. In these models, the fire module calculates direct and indirect carbon emissions from combustion as in the biogeochemical models, but also the potential changes in species composition according to the functional traits associated to resistance to fire and post fire regeneration (Pausas et al. 2004). In these models, fire information can be either inserted from global remote sensing datasets as in the biogeochemical models for historical fire emission assessments, but they have also

been associated with the development of fire risk modules based on more or less complex processes able to reproduce fire hazard based on climatic and anthropogenic ignition and fire spread. A review of existing DGVMs and their related fire modules are presented in table 3. Identifying processes and validating the simulated fire hazards both use global BA product. Landscape fire succession models (LFSM, see Keane et al. (2004) for a review) simulate fire spread at finer scale for local applications but cannot be used yet for global studies due to computer resources and the lack of data for wind downscaling in time and space that drive fire spread (Arca et al., 2007, Duguy et al. 2007). Only few studies yet applied global fire products for coarse resolution fire spread assessment (Anderson et al. 2009, Loboda and Csiszar 2007).

TABLE 3 HERE

For the fire modules embedded in DGVMs, requirements from fire information are fairly coarse, as these models are not able to simulate the exact timing of fires due the high contingency of fires events, but can simulate an average fire regime that has to be compared with actual data. Seasonality, fire number and fire size are the only information requested by this community but validations are usually performed at the biome level or “ecoregion” rather than pixel to pixel so the accuracy in the fire location and date of the burning is low. BA products are used as calibration dataset for fire hazard modules, or as a validation dataset to estimate the validity of these fire modules globally.

Getting a better accuracy on burned areas, exact location and timing is of course a challenge that suits all the vegetation modellers requests as model resolution will increase. However this performance in accuracy has to be closely linked with better performance in land cover mapping as emissions are a function of the burned area, but also by the biomass available for burning. Usually a single land cover map is used e.g. Global Land cover GLC2000 (Bartholomé and Belward 2005), but recent studies pointed out the discrepancy between these products particularly for low density tree cover (Herold et al., 2008, Mc Callum et al., 2006), and efforts are still ongoing for increasing accuracy for land cover maps in vegetation models (Lawrence et al., 2007).

5 Temporal and spatial accuracy of current BA products

5.1 Current weaknesses and failures: a review of evaluation and inter-comparison of BA products

Most peer-reviewed papers reviewed in our analysis identify the benefits of BA products where local ground based statistics are lacking. However, comparisons with high resolution datasets highlight their limitations to characterize small fires (Sa et al., 2007), with a threshold of 105 ha for Hawbaker et al. (2008) or 120 ha for Giglio et al. (2009), or low intensity fires, which are frequent in shifting cultivation (Miettinen et al., 2007) or shrubland fires (De Klerk 2008). Omission and commission errors have been requested early in the BA product development process (Korontzi et al., 2004) and remain a key variable to account for. For example, accuracy of existing BA products range between 70 % and 80% (Kushida et al., 2010, Diagne et al., 2010, Loboda et al., 2007, Schroeder et al., 2008) but can fall down to 40% in some biomes (Giglio et al., 2009) or when using coarser resolution sensors (such as NOAA-AVHRR). Since AVHRR is the only sensor available from 1982 to 1997, finding a balance between length of the time series and accuracy defines the framework for new forthcoming BA products.

As soon as the first BA products have been built and delivered independently, intercomparison exercises could point out the general agreement for the global fire distribution across biomes but with major discrepancies when comparing databases pixel to pixel (Boschetti et al., 2004, Simon et al., 2004, Tansey et al., 2004). Identifying discrepancies between products could point out biomes with more significant weaknesses to account for in modelling error assessments and summarized in table 4. Also, specific studies could identify signal disturbances as heavy clouds during the fire season, depending on data processing algorithm (Roy et al., 2005b, Giglio et al., 2009) more or less robust to the presence of clouds.

TABLE 4

Based on these acknowledged discrepancies between different BA products that are part of the fire detection procedure, Simon et al. (2004) stressed the need for precise user requirement for matching the needs with the technology when necessary. The current BA products limitations reviewed here already bring the technical limitations that have to be overcome before launching finer resolution datasets (De Klerk 2008).

In addition, to refine the acknowledged caveats of existing BA products, recent technical studies aim at developing and testing new outputs, that reveal requirements expected by end-users as fire energy (Boschetti and Roy 2009, Ellicott et al., 2009), low intensity fire for crop residue burning (Punia et al., 2008), fire temperature and fire size (Eckman et al. 2008), or a better fire detection in the tropics (Peng et al., 2008). These requests should be considered carefully for algorithm development and output delivery for a further extensive use of the BA product.

Finally, the latest technologies for advertising, communicating, accessing data and early warning of product delivery, have to be considered interacting with already existing users, but furthermore for a user community not linked with recent fire research activities, as performed by the MODIS team (Davies et al. 2009, Trigg and Roy 2007).

5.2 Forthcoming targets for BA products: a review of requirements identified by previous international science programs

Several international science plans/programs dealing with global fire assessment produced a set of target requirements for fire observation. Here we reviewed the currently undergoing key internationally coordinated science projects/plans that covered the topic of fire. In this section, we extract accuracy targets expressed by the recommendations of the following programmes/reports[1]: GCOS-138 (GCOS 2010, 2011), GTOS T13 (GTOS 2009), GEO Carbon Strategy (Ciais et al. 2010), IGOS Carbon Theme (Ciais et al. 2004), IGOS Land Theme (Townshend et al. 2008), NASA Fire ESDR Whitepaper (Justice et al., 2011)(http://landportal.gsfc.nasa.gov/Documents/ESDR/Fire_Justice_whitepaper.pdf). Existing BA products caveats have been identified and desired requirements for the fire disturbance observation were provided and summarized in table 5. The table includes information from six international programs. The details of target fire observation

[1] Information of these international programs can be found in their web sites: http://www.wmo.int/pages/prog/gcos/index.php?name=News; http://www.fao.org/gtos/; http://www.globalcarbonproject.org/misc/JournalSummaryGEO.htm; http://www.eohandbook.com/igosp/Carbon.htm, http://www.eohandbook.com/igosp/Land.htm,

requirements in these programs are quite different, with GCOS-138 covering much more detailed information, while GEO carbon strategy having only a brief statement.

TABLE 5 HERE

Nevertheless, it should also be confirmed that, a core set of characteristics for global burned area products can be extracted from the proposed requirements by these projects. The global burned area data must be or have:

- Long-term series data for understanding the long-term fire, climate and vegetation interaction. These series can be generated from various sensors but temporal consistence should be assured.
- Temporal stability and consistency, within 5%
- Temporal resolution, daily data with original spatial resolution of the sensor, weekly, 10-day or monthly basis on global scale
- Spatial resolution, originally 250m (or minimum 500m), horizontal resolution 1km acceptable, 0.5 degree or higher resolution on global scale
- Accuracy: highest standard 5% (maximum error of omission and commission), with demonstrated systematic and adequate validation using internationally agreed validation protocol.
- Error tractability and uncertainty characterization, in a manner that can be easily understood and utilized by users in various applications.
- Easy access to data, including auxiliary information and metadata on vegetation cover, burn severity etc

These general recommendationsare not linked to existing capabilities (or those available in the near future from planned satellites). Again in some program reports or documents, it's pointed out proposed requirements can only be met under certain conditions with existing observing system and cannot be met in a systematic way. Therefore the final conclusion would be the design of new burned area data must be centred on these core characteristics or aimed for the highest standard in each characteristic, but with current capabilities, they will not be met systematically.

We found that fire information requirements from global spaceborne observations in international science programs take into account existing capabilities and give some recommendations for improved fire products in the future. But it also should be noted that partly due to the lack of coordination between these programmes (and to their different objectives) their specific requirements vary significantly. In some programmes,

only brief mention is made of specific requirements of burned area products. Also there is generally a lack of complete and in-detail linkage between the recommended requirements and the existing capabilities, or the capabilities that will be available in the near future from planned satellites. Nevertheless a core set of characteristics for global burned area products can be extracted from the proposed requirements by these projects. Getting a continuous time series of BA beginning in 1982 when the first AVHRR data are available is recognised by most programs as critical to get a better understanding of fire - vegetation interactions. This “requirement” implies a temporal stability and consistency between sensors. Once this main goal is achieved, the second most important “requirement” is the need of daily temporal resolution and 250m or better spatial resolution over the globe. This would be the next goal with secondary products aggregated at a weekly or monthly time step and 500m, 1km or 0.5° resolution would be fine for most applications. To decrease misuse of this BA products, bias and random error should be better characterized and documented as well. The design of new burned area data must be centred on these core characteristics and aimed for the highest standard in each characteristic.

6 Identification of requirements for forthcoming BA products: a questionnaire to end-users

6.1 Questionnaire format

We designed a questionnaire (Annexe 1) aiming at identifying and defining requirements for specific applications of burned area products in order to deliver the product consistent with the users’ needs. This questionnaire was sent to targeted end-users from the authors of published papers using BA products, and refines the outcomes of the literature review. End users were classified according to their working country, the field of research they are involved in and their use of BA products within the categories earth observation (EO), modelling (MOD), data assimilation (DA), and other.

In the design of the questionnaire a balance was sought between identifying the “ideal” needs of a user (i.e. irrespective of the technical possibilities that satellite data can principally offer) and the “realistic” needs which take into account the physical limitations of existing sensors. Several questions were directed toward specific product types that can be generated from the remote sensing data. A set of seven pre-defined product types were listed as “plausible products” and users had the opportunity to

formulate different product characteristics or add requirements to the pre-defined set. Five product types were gridded data sets with different spatial and temporal resolution, the other two were “burned patches” (i.e. a list of individual fire events or fire perimeters) and “burned pixel” (i.e. a list of individual satellite sensor pixels classified as burned) data sets. For each type of proposed product an extensive set of possible quality flags and metadata information was suggested and users were asked to rank them in terms of importance for their work.

The questionnaire assessed various accuracy requirements with respect to the burned area detection and quantification, the geolocation and the timing of fire events and the temporal stability of the product. For each aspect of product accuracy, the users were asked to give their requirements for three categories: “ideal” (wish I had this), “reasonable” (would be good if they can do this) and “minimum” (if it is any worse then it becomes useless). These terms can be interpreted similar to the GCOS terminology of “target”, “goal” and “threshold” objectives. User requirements concerning the completeness and robustness of burned area (or fire) detection were queried by asking for acceptable omission and commission errors, respectively. Finally, the users were asked about the file format, metadata conventions and data delivery mechanisms and their preferred way to access the data.

6.2 End-user description

A total of 47 end-users answered the questionnaire. The majority of answers were from researchers working in Europe, followed by people working in North America and South America. Two responses each came from Asia and Australia. This geographical distribution mimics the origin of authors found in the literature survey but with a larger representation of European researchers (Fig. 4a). Among these users, 15 belong to the earth observation (EO) community, 17 to the modelling (MOD) community, 4 to the data assimilation (DA) group and 11 to other areas of expertise, in accordance with the field of research distribution in the literature survey (Fig 4b).

FIGURE 4

The MOD+DA responses exhibit a focus on carbon cycle monitoring and dynamic vegetation modelling, whereas scientists working in the field of atmospheric chemistry tend to belong to the OTHER group. At the interface between the MOD+DA and EO communities are applications related to species migration and the production of land-cover maps. BA products are also widely used for fire hazard monitoring and

assessment of post-fire conditions. Besides the mainstream applications asked for in the questionnaire, burned area products may be used in many fields of research in accordance with the bibliographical review of application. About 50% of users specified the satellite fire products they have been working with in the past and provided comments on the major advantages and disadvantages of these products. The majority of fire products that are presently in use are derived from MODIS, confirming the results from the bibliographical analysis. In the MOD+DA community, several users employ the GFED products (v2, Van der Werf et al. (2006), and v3, Van der Werf et al. (2010)). In the EO community preference is given to the Giglio et al. (2009, 2010), Dempewolf et al., (2007) or Roy et al., (2008) products. Alternatively, the respondents developed their own retrieval products based on MODIS, SPOT/VEGETATION, NOAA/AVHRR or Landsat data. Only few users employ ESA data and if they do, they generally use fire hot spot products rather than burned area.

Main advantages of the currently available fire products are their free availability and the fact that they can be obtained through fast mechanisms of delivery. However, the majority of current products are reported to fall short of the desired accuracy and spatial or temporal resolution. Furthermore, most existing products provide only information on hot spots and have no information on BA. In the case of GFED products the major advantage pointed out by the users is that it has a long time series. The major disadvantages associated with GFED are the ASCII data format, and the fact that this product is not available in real time. In the case of the Giglio et al. (2009, 2010) products, the major advantage and disadvantage is, respectively, the good performance and the lack of global coverage.

6.3 Product Requirements

6.3.1 Type of data products

Fig. 5 shows the score-ranking of the proposed pre-defined product types. Clearly, the users give preference to data products that allow identification of individual fires or regional-scale applications (i.e. relatively well-resolved gridded products). Researchers with coarser resolution models generally prefer gridded products, while scientists applying models at the regional or landscape scale prefer more detailed burned patch or fire pixel information. While several people responded that they prefer to have the option of downloading a coarser-scale product in order to limit the data volume and processing, most say that they would also accommodate the finer resolution products.

Requirements on projection and coordinate system used converged toward the lat/lon coordinate system.

FIGURE 5 HERE

6.3.2 Accuracy requirements

The highest quality standard for the BA product appears as key requirement for future BA products (Table 6). While there is considerable spread from more stringent to much more relaxed quality objectives, the general consensus for the accuracy requirement is: ideal = 5% error, reasonable = 15 % error, minimum = 25 % error. There is no obvious relation of these requirements to the users' model resolution. The dependence of accuracy requirements on scale was mentioned in Roy et al. (2006). Therefore, the questionnaire asked for the required level of accuracy for regional BA and for each single fire. Requirements were tighter for regional BA (10% error) assessments as the users for single fires admit the difficulties to shape fire, even with low resolution images (20% error). When classifying errors into omission and commission errors, several users stated that a certain omission and commission error is acceptable as long as they are both similar. However, the majority of users want to see slightly more stringent requirements applied to commission errors (ideal = 3.7 %, reasonable = 10.6 %, minimum = 17.1 %) than to omission errors (ideal = 4.4%, reasonable = 13.1 %, minimum = 19.1 %). There is no discernible trend of accuracy requirements with model resolution.

TABLE 6 HERE

6.3.3 Geolocation

The question about acceptable geolocation errors provoked rather different responses from the different user communities. Contrary to expectations, the modellers and data assimilation people expressed more stringent requirements than the EO community. Geolocation is of primary importance when the severity of individual burns shall be assessed or when satellite data are being used in realtime to guide fire fighting measures. In the context of earth system modelling (including atmospheric chemistry, carbon cycle and dynamic vegetation modelling), the exact location of a fire is of lesser importance. However, the attribution of a fire to a specific vegetation class (and in smaller scale applications also the orography of the area in which the fire occurred) can matter. Thus, the amount and quality of metadata information that is provided with the fire data will define how well the geolocation of fire pixels must be known. Average user

responses indicated a geolocation accuracy requirement of ideal = 1100 m, reasonable = 2900 m, minimum = 6000 m.

6.3.4 Timing

Users want to be informed about the timing of fire events and they want to know the uncertainty of this quantity. In contrast to the acceptable geolocation error, the MOD+DA communities are prepared to accept a larger timing error (ideal = 2.3 days, reasonable = 6.1 days, minimum = 8.8 days) than the EO community (1 day). This reflects the large proportion of carbon cycle and dynamic vegetation modellers in the MOD+DA community who are less concerned about specific atmospheric transport events. Regarding the temporal stability of the data product quality, less than 15% variability was expected in order to make reasonably accurate assessments of actual fire variability.

6.3.5 Quality indicators

The user responses on desired quality indicators are summarised in table 7. The major concern for all product types is the demand to know which vegetation cover is affected by fires. Date of burn and burn severity are of particular interest to the MOD-DA community while the EO community requests more technical information about the retrieval.

Burned pixel products are primarily of interest to the EO community. These users specifically request metadata information on shadow or smoke contamination and accuracy. Furthermore, they would like to know the probability that a pixel has burned rather than a simple categorisation into burned/unburned. The number of observation days, type of fire, index of vegetation moisture content and pixel value of channel 3.9 µm were listed as additional requested information.

For burned patches products, clearly the most important information is the burned area itself, but most users also want to know the location and time of burning (start and end time) and burn severity. Some interest was also expressed for information concerning the temporal variability of burns within the grid cell. More specific information on the number and sizes of fires within a specified burned area were thought of moderate importance to most users, but ranked relatively high for users at the local scale.

6.3.6 Data format and product dissemination

Among the four proposed data formats ArcGIS shape files, ASCII, HDF5, or netCDF, none stood out as being either strongly favoured or absolutely inadequate for the majority of surveyed users. As some users indicated no interest in ArcGIS or ASCII files, while others don't want to deal with HDF5 or netCDF data, it is recommended to make BA products available in at least two different formats, one from each "family". The responses to the questions about metadata specifications were rather indifferent, albeit several users indicated that the ISO19115 metadata standard with extension to raster format should be adhered to. Most users prefer access to the data via web download or ftp. There is only moderate interest in internet-based mapping or web coverage services and on-demand access is generally not regarded as an attractive option.

6.3.7 Free-form comments

By means of asking the users about the ideal BA product characteristics if there were no restrictions of any kind we wanted to identify the most pressing needs for sensor improvements and test if these are consistent with the relative importance of quality objectives addressed before. Remarkably, the answers were very similar. Many users think there is a lack of high resolution (geostationary) satellites with appropriate sensors for fire monitoring in terms of active fires and mapping of burn scars. These platforms should be equipped with a thermal sensor that does not saturate at typical fire temperatures in order to derive near real-time information about burn severity indices and fire radiative power.

TABLE 7

7 Conclusion on recommendations for BA development and use

We reviewed here the state-of-the-art sources of information related to global burned area applications. From this analysis, we could identify the wide range of end-users, covering research fields outside of the initial goal of these global BA product, mostly focussed on biosphere/atmosphere interactions, and highlighting the increasing use for land management. Based on this result, we then compiled and synthesized the requests for further BA developments for increasing both the fields of research where these data could be used, and a better accuracy when these data are already used in

their present form. We could then provide a synthesized understanding of user requests according to their research interests, the technical limitations to cover these needs and how ongoing project had to find a balance to provide the best-we-can-do product for satisfying most users.

For most fields of research, we identified the need for an increasing length of the time-series with the most consistency across time and successive sensors, as far as errors of commission and omission are conserved or decreased compared to existing products. Fire being a stochastic event, longer time series would provide a more comprehensive fire regime at the regional level for identifying key processes for land managers (as in Moreira et al. 2011) and global process-based fire models (Thonicke et al. 2010). Longer time series will also allow to account for long-term feed backs of fire disturbances on the global budget, as for instance biomass recovery and the its related carbon sink (Chen et al. 2000, Field et al. 1999).

Increasing space and time resolution appear as a second goal to reach as we observe the significant use of active fire counts at high resolution, and should be closely linked with refinement and better accuracy on land cover products. Meeting these requirements will help to fill the gap between the *status quo* and the desired characteristics of fire observation data that may allow more systematic monitoring of fire activity and more accurate estimation of fire emissions. Reaching this goal will also enhance the use of this product in the increasing research community dealing with landscape management plans in fire-prone areas where fire contours are lacking. This includes landscape planning for the reduction of fire risk and subsequent impact on populations, wealth and health, as well as conservation planning.

Therefore, it is recommended that the development of new global burned area data should take into account the target requirements proposed in this study, acknowledging of course the constraints of available observing systems. This review also highlighted the importance of the uncertainty assessment that should be part of forthcoming fire emissions estimates, so that an easy access and fully comprehensible understanding of these uncertainties should be provided. This latter information started to be accounted for in global fire emissions models (Giglio et al. 2010), but still sparsely used at the regional level. We recommend data providers to highlight and describe the uncertainties of their products, and land managers working with these datasets at the regional level with pixel based information to make use of this uncertainty information to prevent any misinterpretations of the data.

The growing topic of increasing accuracy in earth observation products, now relies more on uncertainty assessment by comparing existing datasets (Herold et al. 2008, Frei et al. 2012, Pfeifer et al. 2012), merging products to account for this uncertainty (Knorr et al. 2012) or new algorithm allowing for temporal consistency between sensors across time, leading to similar approaches used for the pre-satellite era where uncertainties are even higher (Mouillot et al. 2005, Meiyappan and Jain 2012).

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Figure Caption

Figure 1: Number of papers references in isiweb using global BA information classified by input product name (a), and using active fire detection (MODIS MOD or MYD product, and ATSR)

Figure 2 - Yearly percentage of peer reviewed papers classified by topic

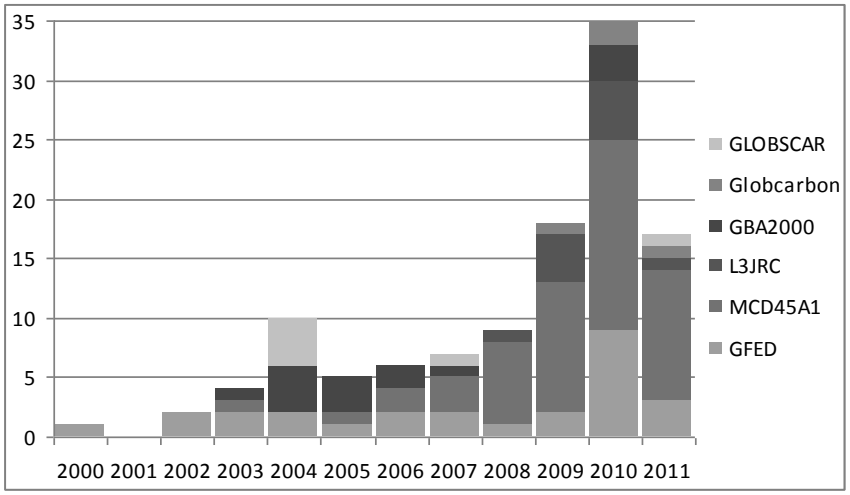
Figure 3 - Yearly percentage of peer reviewed papers using BA products for global or continental

Figure 4 - Regional distribution of questionnaire responses (a) and area of expertise of the participants (b). A total of 47 replies were received.

Figure 5 - Requested product characteristics for BA products - Users were asked to assess usefulness of each product type on a scale from 0 (not useful) to 10 (maximum usefulness). Vertical lines denote the range of answers provided

Figure 1

a)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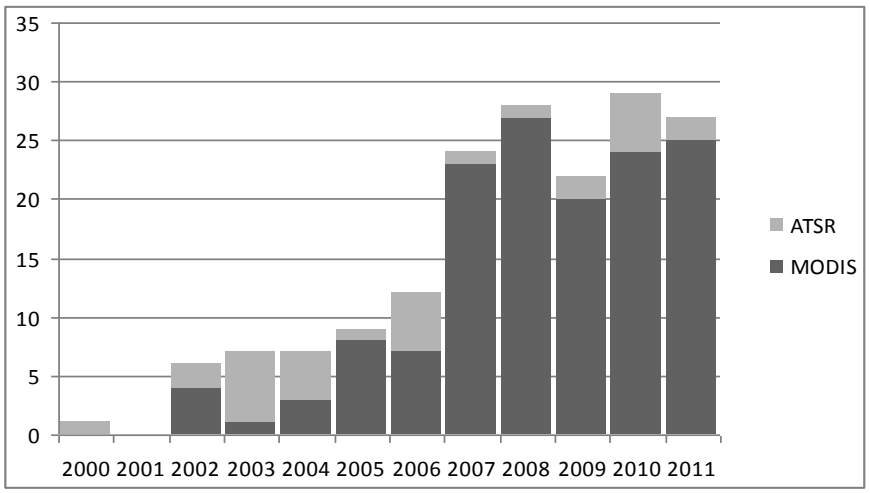
GFED

b)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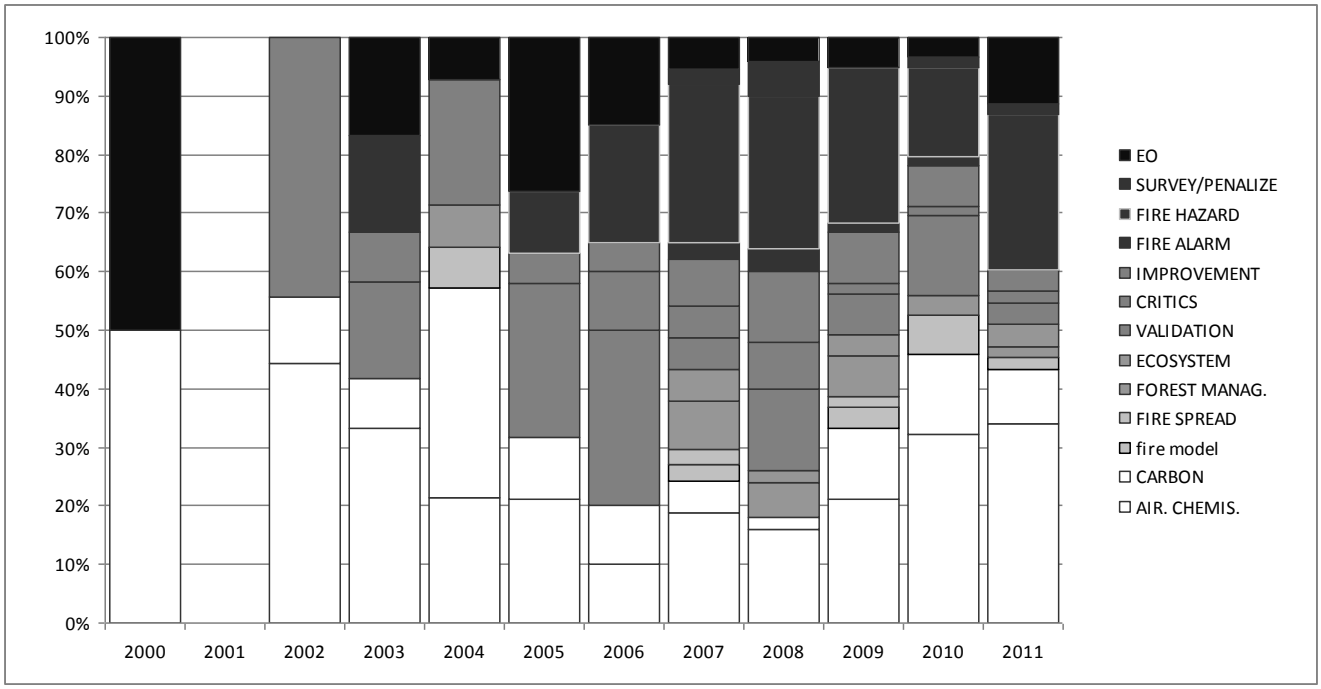
ATSR
MODIS

Figure 2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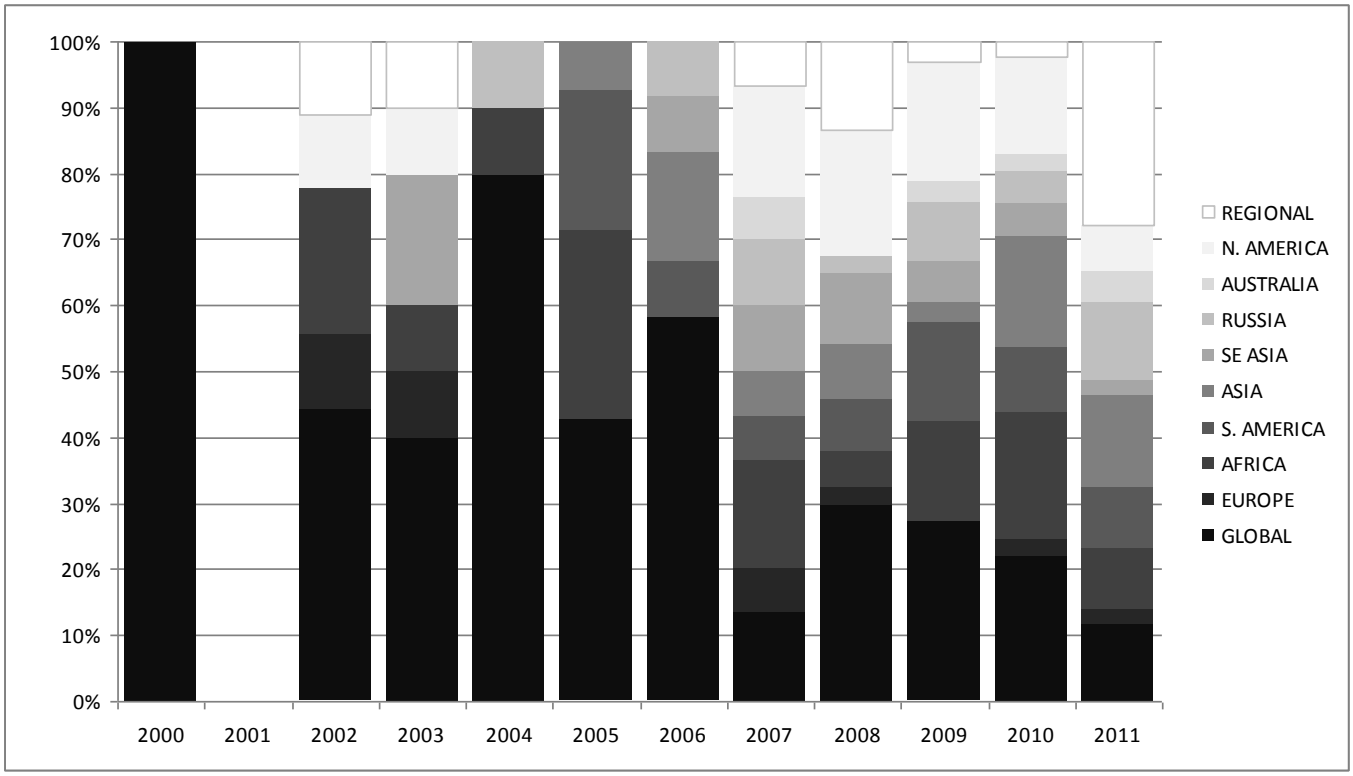
EO
SURVEY/PENALIZE
FIRE HAZARD
FIRE ALARM
IMPROVEMENT
CRITICS
VALIDATION
ECOSYSTEM
FOREST MANAG.
FIRE SPREAD
fire model
CARBON
AIR. CHEMIS.

Figure 3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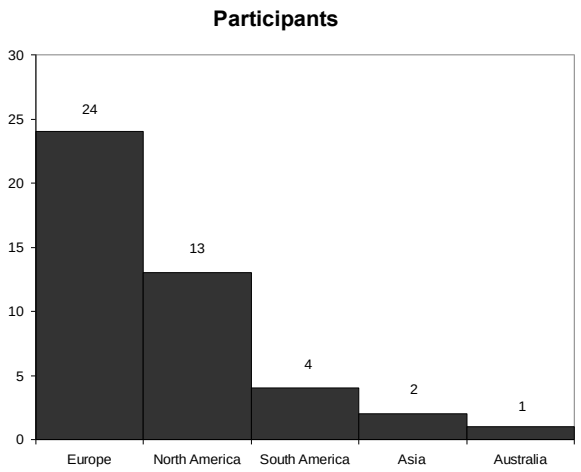
AFRICA
EUROPE
GLOBAL

Figure 4

a)


Participants
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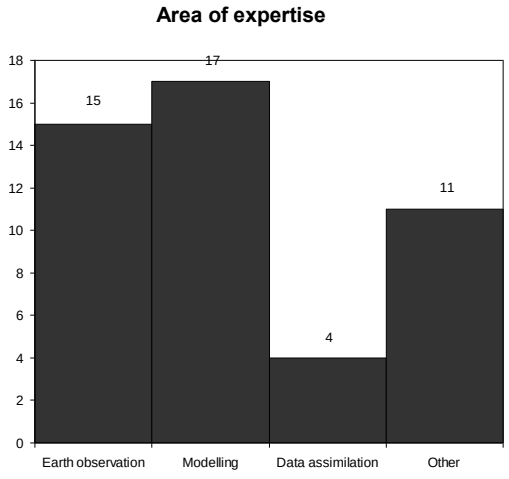
Europe
North America
South America
Asia
Australia

b)


Area of expertise
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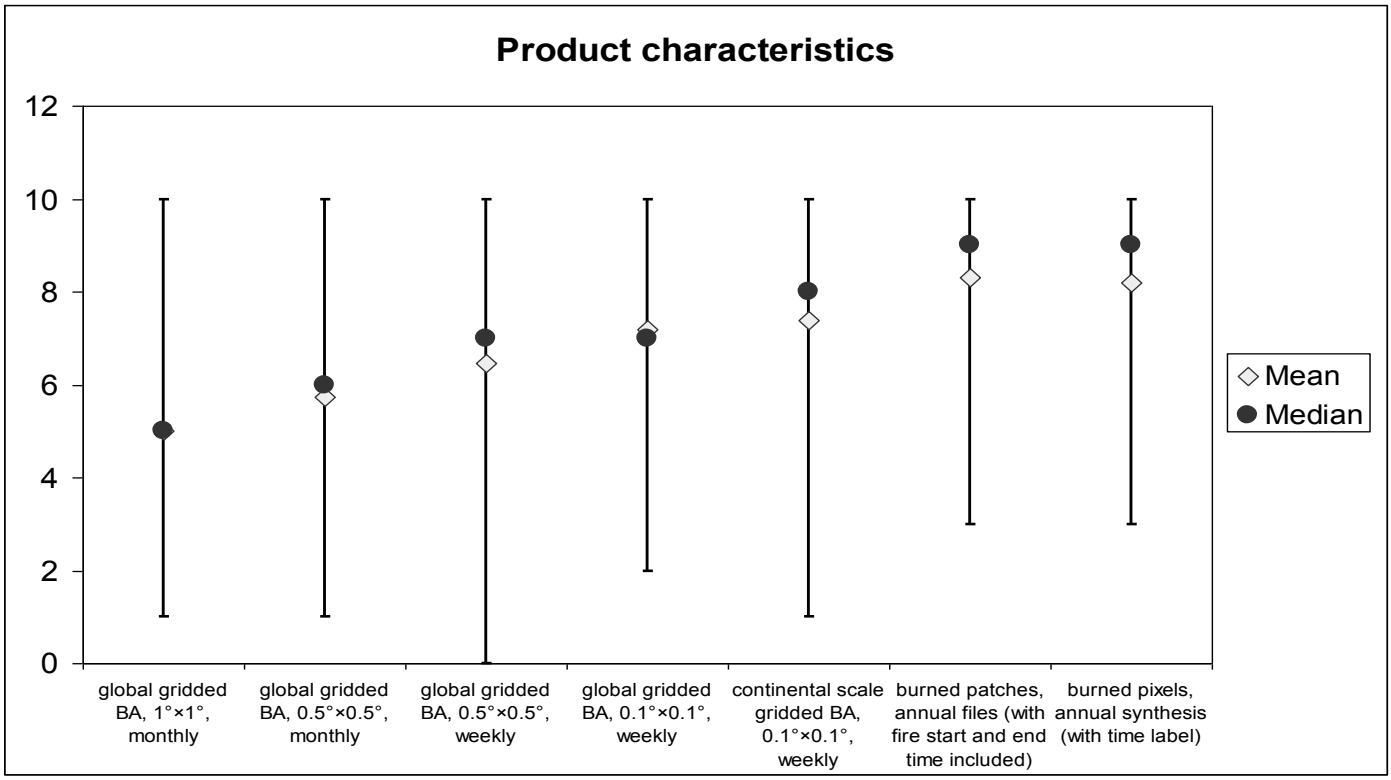
Earth observation
Modelling
Data assimilation
Other

Figure 5


Product characteristics
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global gridded BA, 0.5°×0.5°, monthly
global gridded BA, 0.5°×0.5°, weekly
global gridded BA, 0.1°×0.1°, weekly
continental scale gridded BA, 0.1°×0.1°, weekly
burned patches, annual files (with fire start and end time included)
burned pixels, annual synthesis (with time label)

Table caption:

Table 1: Overview of global burned area dataset from spaceborne remote sensing

Table 2: Global fire models embedded in dynamic vegetation models and using global BA as validation datasets.

Table 3: Satellite burned area algorithms developed for coarse resolution sensors.

Table 4: Synthesis table comparing BA estimates between BA products and compared to ground datasets for major biomes.

Table 5: identified requirements for future BA products from previous user requirement document delivered in international programmes/plans related to BA production or use.

Table 6: spatial and temporal accuracy requirements for future BA products based on questionnaire to end-users

Table 7: Additional quality information expected for future BA products based on questionnaire to end users (++: high interest, +:fair interest, 0: no opinion, -: no interest)

Name of Dataset	***Time span***	***Satellite***	***Spatial resolution***	***Temporal resolution***	***Status***	***Development purpose***	***Source***
GFED3	*1996.07-present*	*MODIS 500 m, TRIM/VIRS, ATSR*	*0.5d x 0.5d*	*Monthly*	*Operational*	*Atmospheric and bio-geochemical models*	*Giglio et al. 2010*
MCD45A1	*2000-2009*	*MODIS 500 m*	*500 m*	*Monthly*	*Operational*	*general purpose*	*Roy et al. 2008*
L3JRC	*2000-2007*	*SPOT VEGETATION*	*1 km*	*Daily*	*Finished*	*general purpose*	*Tansey et al. 2008*
GLOBCARBON	*1998.04-2007.12*	*SPOT VEGETATION, ATSR-2, AATSR*	*1 km, 0.25 or 0.5 degree*	*Monthly*	*Finished*	*targeted for global carbon cycling and climate modelling use*	*Plummer et al. 2006*
GBS	*1982-1999*	NOAA-AVHRR GAC 8 km data	*8 km*	*Weekly*	*Finished*	*Globally consistent records of global fire activity.*	*Carmona-Moreno et al. 2005*
GLOBSCAR	*> 2000*	*ERS2-ATSR2*	*1 km*	*Monthly*	*Finished*	*producing global incremental monthly maps of burned areas*	*Simon et al. 2004*
GBA2000	*2000*	*SPOT VEGETATION*	*1 km*	*Monthly*	*Finished*		*Tansey et al. 2004*

Table1

Table 3

Fire Module name	Fire processes	DGVM	reference
TRIFFID	Constant	TRIFFID	Cox (2001)
	Fire occurrence Empirical based on Litter moisture Litter amount No BA no c emissions	IBIS ED VeGAS-DGVM SDGVM	Kucharik (2000) Moorcroft et al. (2001) Zeng et al. (2010) Woodward et al. (1995) Woodward and lomas (2004) Bond et al. (2003)
CTEM fire (Arora and boer 2005)	Fire rate and spread, prescribed consumption and mortality Wind speed and soil moist	CTEM	Arora (2003)
Glob FIRM (Thonicke et al. 2001)		SEIB DGVM CLM3.0 ORCHIDEE GOLM DGVM CLM4, CNDV LPJ	Sato et al. (2007) Levis et al. (2004) Krinner et al. (2005) Dai et al. (2003) Oleson et al. (2010) Sitch et al. (2003)
SPITFIRE (Thonicke et al. 2010)	Lightening, human causes	LPJ LPJ guess ORCHIDEE	Sitch et al. (2003) Smith et al. (2001) Krinner et al. (2005)
MC fire (Lenihan and Neilson 1998)	Fire – vegetation fire spread and fire effect on mortality based on drought index and time since last fire	MC1 DGVM	Bachelet et al. (2001)
Reg firm	Regional Climate fire danger Ignition spread	LPJ	Venevsky et al. 2002

Table 2

Reference	Method	Satellite sensor(s)	Domain	Period covered
Kasischke and French, 1995	15-day NDVI composite differences	AVHRR	Alaska	1990-1991
Fernández et al., 1997	10-day NDVI maximum regression and differencing	AVHRR	Spain	1993-1994
Eva and Lambin, 1998a	SWIR reflectance change and temperature increase	ATSR	Africa	1994-1995
Barbosa et al., 1999	daily 5-km imagery analysis of reflectance, brightness temperature and vegetation index changes	AVHRR	Africa	1981-1983 and 1985-1991
Roy et al., 1999	temporal composite of a spectral index (near infrared minus reflective component of middle infrared channel) for pixels with active fire detection	AVHRR	southern Africa	1 month in 1989
Fraser et al., 2000	10-day NDVI composite differencing combined with active fire detection	AVHRR	Canada	1995-1996
Pereira et al., 2000	classification trees of (daily?) thermal, albedo and vegetation index imagery	AVHRR	central Africa and Iberia	
Isaev et al., 2002	NDVI differencing	SPOT-HRSVIR and RESURS-O/MSU-E	Siberia (individual fire)	1997
Brivio et al., 2003	Neural network classification scheme	SPOT-VEGETATION	sub-Saharan Africa	2000
Fraser et al., 2004	logistic regression model on 10-day composites of vegetation index and subsequent region-growing	SPOT-VEGETATION	Canada	1998-2000
Gerard et al., 2003	NDSWIR differencing, classification of older burn scars	SPOT-VEGETATION	Canada	1998
Stroppiana et al., 2003	classification trees of 10-day composite thermal, albedo and vegetation index imagery	SPOT-VEGETATION	northern Australia	1999
Zhang et al., 2003	multi-temporal spectral reflectance differencing criteria	SPOT-VEGETATION	Russian Federation	2001
Pu et al., 2004	similar to Fraser et al., 2000	AVHRR	western North America	
Simon et al., 2004	two algorithms: (1) contextual NIR reflectance and (TIR) brightness temperature change, (2) series of fixed thresholds	ATSR-2 and AATSR	global	2000
Sukhinin et al., 2004	similar to Fraser et al., 2000, but burn scar mapping based on post fire scenes only	AVHRR	Siberia	1995-2003
Tansey et al., 2004	nine different regional algorithms analysing surface reflectance changes	SPOT-VEGETATION	global	2000
Carmona-Moreno et al., 2005	variant of Barbosa et al., 1999 algorithm	AVHRR	global	1982-1999
Roy et al., 2005b	deviations from bi-directional reflectance model expected reflectance	MODIS	test regions on several continents	2002
George et al., 2006	normalized shortwave IR difference and NDVI differences, active fire detection for dating	MODIS	central Russia	1992-2003
Giglio et al., 2006	regional regression trees of active fire detections correlated with persistent changes in vegetation index and NIR reflectance (extension of Roy et al., 1999)	MODIS	global	2000-2005
Loboda et al., 2007	8-day surface reflectance composite changes (normalized burned ratio differencing) and active fire masks	MODIS	test regions in North America and Siberia	2001-2005
Pu et al., 2007	similar to Fraser et al., 2003, combined with active fire detection	AVHRR	North America	1989-2000
Tansey et al., 2008	“one of GBA-2000” algorithms	SPOT-VEGETATION	global	2000-2007
Giglio et al., 2009, Giglio et al., 2010	similar to Giglio et al., 2006	MODIS	global	2001-2009

Table 4

BOREAL/TEMP	GFED2	GFED*3*	*L3JRC*	*GLOBCARBON*	*MCD45A1*	*GBS*	*data*
GFED2	=						
GFED3		=	+	+	=		+
L3JRC		-	=		-		-
GLOBCARBON		-		=	-		-
MCD45A1		=	+	+	=	*6*	+
GBS							
					- canada, USA (4, 5)		
					+ russia		
Data		-	*++ NA (4,5)*	+	*= china (3,1,4)*		=
SAVANNAS							
GFED2	=						
GFED3		=	*-50%*	*-50%*			
L3JRC		*+50%*	=		*+50%*		
GLOBCARBON		*+50%*		=	*+50%*		
		=					
		Except Africa					
MCD45A1		*australia*	*-50%*	*-50%*	=		
			2	*-2*			
data			*-1*	*1*	*=/-(2)*		=
TROPICAL							
GFED2	=						
GFED3		=					
L3JRC		*100%*	=				
GLOBCARBON		*100%*		=			
MCD45A1		*100%*			=		
data							=

(1) Giglio et al. (2010)
(2) Roy and boschetti (2009)
(3) Chang and song (2009)
(4) Kasischke et al. (2011)
(5) Loboda et al. (2011)
(6) Camona-moreno etal (2005)

Table 5

			GCOS-138	GTOS	GEO carbon strategy	IGOS carbon theme	IGOS land theme	NASA
requirements	spatial resolution		250-500m	250m		<200m		500m + local 30m + aggregation 0,5°
	temporal resolution		week/10-day/monthly	daily		monthly		2/3 days, month
	accuracy	commision	5%	5%				
		omission	5%	5%				
	temporal stability		5% climate standard	5%		Continuity		consistency
	period covered		as long as possible 1982 with AVHRR				long term	long term with AVHRR
	data format		standardization of data format					
	Error characterization		Error traceability		better validation		better validation with CEOS protocol	
	Calibration and Validation		calibration/validation effort					
			international agreed validation protocol					
			calibration NIR, VIS, SWIR within 2% over lifetime					calibration NIR, Vis, SWIR
	Other BA information		Date of burn information			provide info on ground fires		
						combine ground observation when possible		

Table 6

		tolerable error (%)		Omission (%)		Commission (%)		Geolocation (m)		Timing (days)	
		mean	min-max	mean	min-max	mean	min-max	mean	min-max	mean	min-max
ideal	ALL	5	0-20	5	0-10	4	0-20	1000	0-20000	2	0-20
	MOD+DA	4,5		5		3,5		250		2,5	
	EO	5,5		5		4,5		1000		1,5	
reasonnable	ALL	15	(5-30)	12	0-40	10	0-30	2000	5-50000	10	1-150
	MOD+DA	15		12		10		500		11	
	EO	15		12		10		2000		5	
minimum	ALL	25	(10-50)	20	0-50	17		5000	8-100000	15	2-200
	MOD+DA	25		20		16		2000		20	
	EO	25		20		18		10000		10	

Table 7

	pixel based		*patch*		*grid*	
	MOD DA	*EO*	*MOD DA*	*EO*	*MOD DA*	*EO*
burn severity	++	+			++	+
date of burn detection	++	++	'++	++		
cloud contamination	*0*	+				
cloud shadow contamination	*0*	+				
topographic shadow	-	+				
smoke	*0*	+				
snow	-	*0*				
water	-	*0*				
dominant vegetation cover	++	+	++	+	++	+
confidence level	+	++				
geolocation			++	+		
burnd area			++	++		
sensor			*0*	+		
Algorithm			*0*	+		
temporal variability					+	+
omission					+	++
commission					+	++

Annex 1 : questionnaire sent to end-users

1) User identification

If you prefer to stay anonymous you can do so, but please provide your institution and area of expertise in any case so that we can better link your requirements with specific user communities. If you think you belong to more than one user community with different requirements, please fill in two forms (don't mix use cases).

Name		**e-mail**	
Institution		**Phone/Fax**	
Position			
Area of expertise	□ Earth observation □ Modelling □ Data assimilation □ Other	**Available for further contacts?** □ YES □ NO	

If you work on Earth observations, please indicate type of measurement, platform, interest in fire data:

If you work with models or data assimilation, please indicate type of model, domain (global/regional/…), typical resolution, interest in fire data. Also in this box please tell us how you are using fire data. Please insert links to relevant web pages if appropriate:

If you think you belong to a different user community, please specify:

2) Product Use

Mark with an '**X**' if the BA product is needed for the application and/or comment.

End-users	Applications	
Atmospheric Chemistry Community	Monitoring (i.e. observations and data assimilation) of trace gases, aerosols and emissions	
	Operational use in atmospheric composition monitoring	
	Modelling of atmospheric chemistry	
	Air pollution control	
	Other (please specify)	
Climate-Vegetation Community	Monitoring and modelling of carbon fluxes	
	Vegetation dynamics (seasonal, interannual)	
	Species migration	
	Production of land cover maps	
	Other (please specify)	
Earth Observation Community	Production of other ECVs	
Natural Hazard Prevention Community	Fire hazard monitoring	
	Desertification	
	Other (please specify)	
Forest Services	Forest management	
	Post-fire vegetation conditions	
	Other (please specify)	

If you have used any other burned area products in your activities, please give some references and list what were the main advantages and limitations of each one:

3) Product characteristics

In order to take into account the heritage of existing satellite fire products, we are proposing a few examples for the type of product that could be generated. Please indicate on a scale from 1 (very low) to 10 (extremely useful) the value that each of these products would have for your work. If you don't see any relevance of a specific product you can either leave the line blank or enter 0. Please try to establish a ranking so that not more than two product types are marked with the same grade.

Please note: data format and metadata requests will be addressed below.

Product type	**Relevance (0..10)**
global gridded BA, 1°×1°, monthly, lat-lon coordinates	
global gridded BA, 0.5°×0.5°, monthly, lat-lon coordinates	
global gridded BA, 0.5°×0.5°, weekly, lat-lon coordinates	
global gridded BA, 0.1°×0.1°, weekly, lat-lon coordinates	
continental scale gridded BA, 0.1°×0.1°, weekly continent/region: coordinate system:	
burned patches, annual files (with fire start and end time included)	
burned pixels, annual synthesis (with time label)	
Own characteristics (please use categories similar to the above to describe your product requirements)	

4) Product Accuracy and Quality Control

Please try to estimate your accuracy requirements in the three categories “ideal” (wish I had this), “reasonable” (would be good if they can do this) and “minimum” (if it is any worse then this it becomes useless):

Product Accuracy	Ideal	Reasonable	Minimum
Burned area (in %)			
Completeness (omission errors in %)			
False attributions (commission errors in %)			
Geolocation Accuracy (in m)			
Temporal accuracy* (in days)			
Temporal stability (in % per annum)			
Other (please specify)			

* temporal accuracy means correctness of time label. Some burn scars can be shielded by clouds for a while before they are detected, or satellite overpasses don’t allow for an earlier detection. If your requirements are not stringent in this area, this may also ease processing requirements.

Have you used accuracy information of fire products previously? If so, please describe your experiences and the sensitivity of your model/application to product errors (e.g. reference to a publication). If you have not yet used accuracy information of fire products, please state why not.

5) Metadata and Quality Flags

Please indicate the metadata information you wish to see attached to the data. If you request a different kind of information please enter a note below the table.

Type of Product	Options	Important	Nice to have	Unimportant
Pixel-based	Burn severity (low, moderate, high, very high)			
	Date of burn detection			
	Cloud contamination			
	Cloud shadow contamination			
	Topographic shadow contamination			
	Smoke contamination			
	Snow contamination			
	Water contamination			
	Dominant vegetation cover			
	Confidence level			
	Other (please specify)			
Burned patches	Geolocation of centre			
	Burned area			
	Start date of burn			
	End date of burn			
	Dominant vegetation cover			
	Dominant vegetation cover fraction			
	Sensor			
	Algorithm Code			
	Other (please specify)			
Gridded data	Dominant vegetation cover			
	Dominant vegetation cover fraction			
	Temporal variability index			
	Burn severity classes (1,2,3) (% of each class)			
	Omission error estimate			
	Commission error estimate			
	Other (please specify)			

Notes:

6) Data Format and Product Dissemination

File format	Ideal	Reasonable	Minimum
ASCII Files			
GEOTIFF			
ArcGIS shape			
HDF5			
netcdf			
Other (please specify)			
Metadata format:			
Standard ISO 19115 with extension to raster format			
METAFOR			
CF			

Mechanisms	Ideal	Reasonable	Minimum
Internet web mapping service			
Web download			
Web coverage service			
FTP			
On-demand			
Other (please specify)			

Are you accustomed to downloading data from one of the following portals?

 ESA facilities

 Global Master Directory

7) Other issues

Here is room for any other comments or suggestions you might have:

8) Outlook

Provided that the final burned area product meets the above proposed specifications, how would you estimate the potential benefits for improvements in your field of application/research?

Would you be interested to get involved in the testing of the new burned area product?

 YES

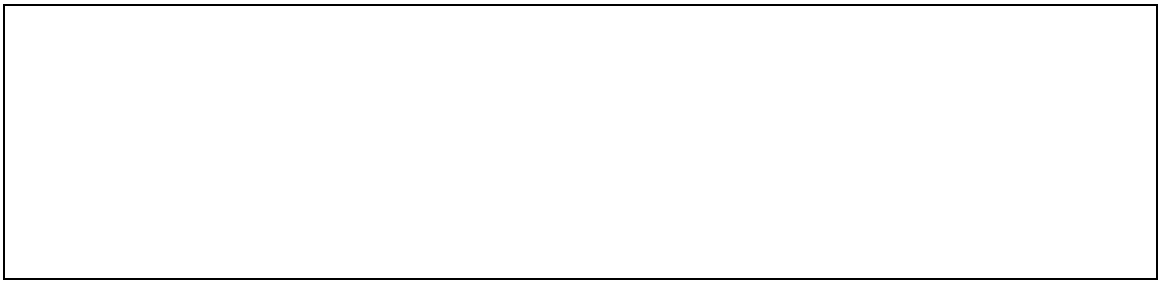
 NO

Would you be interested in a user workshop on the new product should such a meeting be organized?

 YES

 NO

If you could influence the design of new satellite instruments and define the fire product characteristics, what kind of fire data products would you like to see (please use the categories above to describe your optimum product):



1 Annex 2: list of references using spaceborne remote sensing BA products or active
2 fires, and their corresponding fields for BA or active fire product's name, scale of
3 application, biome studied and field of research.

Reference		BA products						active fire counts + others				Scale of application	CONTINENTAL									BIOMES						scientific application								
		L3JRC	GFED	MCD45A1	GBS	GBA2000	GLOBCARBON	GLOBSCAR	MOD14/MYD14	ATSR	NOAA AVHRR	GOES WFABBA	ASTER	GLOBAL	North America	Europe	Africa	south America	Asia	south east Asia	Russia	Asutralia	landscape region	boreal forest	temperature forest	mediterranean	savanna	temp. Grassland	trop. Forest	agriculture	air chemistry	carbone budget	fire model	forest manage	ecosystem func	fire hazard	fire spread	validation	improvement	earth observation	fire alarm	survey/penalize
Giglio et al.	2000	x												X																								x		
Goloub and Arino	2000									X				X																x										
Barbosa et al.	2002								X							X							x			x										+				
Ji and Stocker a	2002	x												x																x										
Ji and Stocker b	2002	x												X																X										
Justice et al.	2002								X								X									x										+				
Roy et al.	2002								X								X									x										+				
Schultz	2002									X				X																x										
Schultz et al.	2002									X				X																x	x									
Seielstad et al.	2002								X						X									x												+				
Brivio et al.	2003					X											X									x										+				
Duncan et al. b	2003									X				X									X							x										
Duncan et al. a	2003									X										X								x		X										
Generoso et al.	2003									X				X																x										X
Giglio et al.a	2003	x												X																								x		
Giglio et al.b	2003								X					X																								x		
Kasischke et al.	2003									X					X									x												-				
Kehla et al.	2003									X						X								X																X
Pereira	2003									X							X										X	X										X		
Pochanart et al.	2003									X										X								x		x										
Van der Werf et al.	2003	x												x																	x									
Boschetti et al.	2004					X		X		X				X																						+				
Hoelzeman et al.	2004							X						X																X		x								
Ito and Penner	2004					x				x				X																	X									
Kasischke and Penner	2004	x				x		x						x																	x									
Korontzi et al.	2004								X	X	x						X									x				X						+				
Kovacs et al.	2004								X												X			x									x							
Li et al.	2004								X					X																							+				
Simon et al.	2004							X		X				X																x	x									
Tansey et al.	2004					X								X																									X	
Van der Werf et al.	2004	x												x																	x									
Alleaume et al.	2005								X								X									x				X					X					
Cardoso et al.	2005								X									X										x								-				
Carmona-Moreno et al	2005				X									X																								x		
Csiszar et al.	2005								X					X																								X		
Ito and Penner	2005					X								X																X	x									
Korontzi et al.	2005					X											X									x				x										

Michel et al.	2005					X														X														x											
Morisette et al. A	2005								X				x				X												X											+				
Morisette et al. B	2005								X									X													x									+				
Mouillot and Field	2005									x				x																												x		
Randerson et al.	2005		X											X																					X									
Roy et al. A	2005								X					X																										+		x		
Roy et al. B	2005			x					X								X												x											+		x		
Schroeder	2005								X									X											x										x					
Boschetti et al.	2006					x								x																										+		X		
Bradley and Millington	2006		x			X				X								X											x		x	x						x		-				
Chen et al.	2006								X										X																						x			
Csiszar et al.	2006								X												X					X														X				
Fuller and Murphy	2006									X										X											X							X						
Giglio et al. a	2006			X					X					X																										+		x		
Giglio et al. b	2006								X					X																								x		+		x		
Korontzi et al.	2006								X					X																		x						x						
Mota et al.	2006									X				X																										-				
Mouillot et al.	2006		x							x				x																					x									
Van der Werf et al	2006			X					X	X				X																			x	x										
Venkataraman et al.	2006								X										X										x				x											
Arino & Paganini	2007									X				X																											x			
Bartalev et al.	2007								X												X					x												x		+	X			
Chand et al.	2007								x										X										X									x						
Chen et al.	2007								X										X								x											x						
Giglio	2007		x						X					X																												x		
Ito & Akimoto	2007			x													X												x				x											
Jain	2007		X			X		X						X																				x	x									
Kalashnikova et al.	2007								X													X							x				x											
Koren et al.	2007										X							X													x							x						
Langner et al.	2007								X											X											x					x	x							
Loboda and Csiszar a	2007								X												X					X												x	x					
Loboda and Csiszar b	2007								X												X					x												x						
Loboda et al.	2007								X					X																										+				
Mac Carty et al.	2007								X						X																	x						x						
Mazzoni et al.	2007								X						X											x	x					x	x											
Miettinen et al.	2007			x					X											X											x							x						
Pu et al.	2007										X				X											x	x											X						
Roy et al.	2007								X						X											x	x						x											
Sa et al.	2007								x								x												x													x		
Saarikoski et al.	2007								X							X											x						x											
Serneels et al.	2007								X								X												X								X							
Smith et al.	2007								X													X							x			x						x						
Stohl et al.	2007								X							X																x	x											
Trigg and Roy	2007			x					X								X												x							x								
Turquety et al.	2007								X						X											x							x											
Wright et al.	2007								X								X	X		X											x					x								x
Achard et al.	2008								x												x					x																		
Al-Saadi et al.	2008			x								X			X											x	x						x											
Boschetti and Roy	2008								X					X																								X						
Boschetti et al.	2008			X												X									X			X										X						
Calado & Dacamara	2008								X		X														X			X												+				
Chuvieco et al. a	2008										X				X											x																x		
Chuvieco et al.b	2008								X					X																								x						
De Klerk	2008								X																x				x											-				
Eckman et al.	2008								X				X	X											X								x							-	x			
Giglio et al.	2008								x				X	X																										+				
Hawbaker et al.	2008								X						X												x													-				
Henderson et al.	2008								X					X																			X											
Huesca et al.	2008								X																x			x								x								

Ichoku et al.	2008							X					X																												X		
Korontzi et al.	2008							X						X																	X				x		x						X
LePage et al.	2008								X				X															X									x						
Mac Carty et al.	2008							X						X																	X						X						
Mari et al.	2008							X								X												x				x											
Moffet et al.	2008							X									X											x				x											
Morton et al.	2008							X									X													x						x	x						
Peng et al.	2008							X											X											x									-	X			
Prasad et al.	2008							X		X								X										x		x							X						
Rinsland et al.	2008							X											X											x		X											
Roberts & Wooster	2008		X	X					X								x												x					x										
Robbins et al.	2008							X									X													x							X						X
Roy et al.	2008			X					X					X																											X	x		
Schroeder et al.	2008							X			X		x																										+				
Tansey et al.a	2008									x									X											x										x			
Tansey et al.b	2008	X												X																												x		
Vadrevu et al	2008								X									X										x									x						
Van der Werf et al a	2008			x																x											X							X						
Van der Werf et al. B	2008			x					x		x			x																								X						
Wang et al.	2008							X																X		X	x										x						
Zeng et al.	2008							X						X												x									x								
Zhang et al.	2008										X			X												x		x			x	x										X	
Anderson et al.	2009							X		X				X														X									X	x					
Archibald et al.	2009			x													X											x	x							x	x	x						
Armenteras et al.	2009							X									x													x		X					x						
Barstch et al.	2009			x						X	X										X					x												x						
Boschetti and Roy	2009			x					X					X																											x	x		
Chang and Song	2009	X		x										X																										+				
Davies et al.	2009							X					X																											x	x	x	
Dirksen et al.	2009			X																		X							X				X											
Ellicott et al.	2009							X					X																			X	X										
Fiebig et al.	2009							X									X															x											
Freeborn et al.	2009							X								X												X									x						
Giglio et al.	2009			x										X																										+	x	x		
Huang et al.	2009			x							X		X								X					X							X	X										
Hyer and Reid	2009							X			X						X													x			X										
Krawchuk et al.	2009							x	X				X																								X						
Langner and Siegert	2009									X									X											X							x						
Lehsten et al.	2009	X															X												X				x	x	x									
Lin et al.	2009							X											X											X		x											
Loboda	2009							X												X					x										x		x						
Mac Carty et al.	2009							X						X										X							x						X						
Maeda et al.	2009							X									X													x							x						
Reid et al.	2009			x								X		X																			x											
Ressl et al.	2009							X		X							X											x							x		x						
Roy and Boschetti	2009	X		x			x										X												x											+				
Siljander et al.	2009			X					X								X												X									X						
Soja et al.	2009							X			X			X										X	x	x					X	X	x				x						
Song et al.	2009	X		x															X													x		x				x						
Stavrakou et al.a	2009		X											X																			X											
Stravakou et al.b	2009		X											X																			x											
Tonini et al.	2009							X						X														x							x	x	X						
Urbanski et al.	2009							X						X											x	x														x			
Uriarte et al.	2009									X														x							x	X											
Van der Werf et al. 2009	2009							X									X													x			x	x	x								
Wang et al.	2009							X						X											X	X					X								-	X			
Archibald et al.	2010			x													X								X				x									x						
Biswajeet and Hamid	2010							X		X									X											x												x	

Boschetti et al.	2010			x					X					X																										+				
Bromley	2010								X								X												X															x
Chang and Song	2010	X		X																x										x		x										
Chedin et al.	2010		X											x																		x										
Cherian et al.	2010								X										X										x				X											
Devineau et al.	2010			X					X								X												x								x	x						
Diagne et al.	2010								X	x							X												X									x		+				
Dlamini	2010								X								X												X									X						
Dubinin et al.	2010			x							X										X									x								x		+				
Eckman et al.	2010								X								X												x												x	x		
Fan et al.	2010								X										X													x	x											
Giglio et al.	2010	X	X	x			x	X	X	X				X																				x							x	x		
Henderson et al.	2010			x											X											x							x							+				
In and Kim	2010								X										X							x	x						x							-				
Kloster et al.	2010	x	x			x								X																				x	x									
Kushida et al.	2010								X										X								x			x										+	X			
Lehsten et al.	2010			X													X												x						x									
LePage et al.	2010								X									X													x					x	X	X						
Li et al. A	2010								x										x								x					x	x											
Li et al. B	2010								X										X													x	X											
Liousse et al	2010	x	x											x																			x	x										
Longo et al.	2010			x														X											x		x		x											
Merino de Miguel et al.	2010								X																x			x												+				
Mieville et al.	2010					X				X				X																			x											
Peterson et al.	2010								X						X											x	x											x						
Romero-Ruiz et al.	2010			x														X											X									x						
Russel-Smith et al.	2010								X													X							X									x						
Singh et al.	2010								X						X													x					X											
Song et al.	2010			x															X								x		x				X	x										
Stroppiana et al.	2010		X	x					X	X							X												x		x		x	x						+				
Takahata et al.	2010								X										X								x		x									x						
Thonicke et al.	2010	X	X	X	X	X								X																				X	X									
Ulevicius et al.	2010								X							X										x							X											
Urban et al	2010			x			x								x											x								x										
Van der Werf et al.	2010		x	x						X				X																				x	x									
Vivchar et al.	2010			x																	X					X							X											
Xu et al.	2010		X						X						X			X								x	x		x				x								x			
Yurganov et al.	2010		x											x																			x											
zhang et al.	2010								X						X												x						x											
Ali et al.	2011								x																x													x						
Ambrose et al.	2011								x																x		x						x											
Ardakani et al.	2011								x																x													x						
Armanteras-pascual	2011			x					x																x						x							x						
Badarinath et al.	2011								X										X																							x		
Barbero et al.	2011								X	x															x						x		x											
Bastarrika et al.	2011								x							x												x													x	x		
Chen et al.	2011								x										x											x								x						
DiBella et al.	2011								x									x									x											x						
Dubinin et al.	2011			x																	x					x												X						
Fernandes et al.	2011								x								x								X						X							x						
Fokeeva et al.	2011								x												x					x							x											
Gomez and Martin	2011			x																					x			x													x	x		
He et al.	2011								x										x														x											
Heinold et al.	2011								x								x																x											
Huang et al.	2011			x															x						x						x		x											
Kasischke et al.	2011	x	x				x	x	x						x												x						x											
Krawchuk and Moritz	2011								X					X											x													x						
Kumar et al.	2011								x								x					X											x											
Kumar et al. b	2011								x																x								x											

Loboda et al.	2011		x												x	x										x	
Maeda et al.	2011			x						x								x							x		
Mc Carty et al.	2011		x					X											x	x							
Miettinen et al.	2011			X								X						x							x		
Morton et al.	2011		x							X								x					x	x			
Mu et al.	2011	x				x	x													x	x						
Prentice et al.	2011	x					x											x			x	x					
Redo et al	2011				X					X								x									x
Roberts et al.	2011		x						x								x			x							
Schwalm et al.	2011		x				x														x						
Sessions	2011			x		x							x			x				x							
Singh and Panigrahy	2011			x							x								x	x	x						
Small et al.	2011			x										x						x							
Tulbure et al.	2011			X				X											x					x	x		
Vadrevu et al	2011			X							X								x	x					x		
Vasileva	2011		x										X			x				x	x					x	
Vivchar et al.	2011		x										x												x	x	
Waring et al.	2011			x				x								x									x		
Zhang	2011			X			X													x							

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