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Wildland fire emissions, carbon, and climate: Wildland fire detection and burned area in the United States

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ABSTRACT

Biomass burning is a major source of greenhouse gases, aerosols, black carbon, and atmospheric pollutants that affects regional and global climate and air quality. The spatial and temporal extent of fires and the size of burned areas are critical parameters in the estimation of fire emissions. Tremendous efforts have been made in the past 12 years to characterize the variability of fire locations and burned areas using high frequency satellite observations (e.g., MODIS, GOES) and improved ground-based reports. We describe and compare the major global and regional (e.g., western United States) burned area products and summarize their major findings. The various ground-based reporting systems and the data quality on fire characteristics and burned areas are examined, and we summarize the major knowledge gaps and recommend further improvements in our understanding of fire activity and burned areas.

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1. Introduction

Wildland fires can be an important source of greenhouse gases as well as black carbon emissions that have been shown to play an important role in the climate system (IPCC, 2007). Additionally, wildland fire emissions can have substantial impacts on air quality. For these reasons, obtaining accurate and detailed inventories of fire occurrence is important. Information on the spatial and temporal distribution of burned areas and fire emissions is also essential for modeling atmospheric photochemistry and the formation of tropospheric ozone, which is also a greenhouse gas (GHG). Because fire emissions are highly variable in time and space and depend on a variety of vegetation and atmospheric conditions, assessing the relative magnitude of climate response to fire emissions compared to other emission sources of GHG, aerosols, and black carbon to the atmosphere is difficult (e.g., van der Werf et al., 2010). The information on fire locations occurring for a period of time (fire activity) and the area of biomass impacted by that fire activity (burned area) are imperative pathways to quantify regional and global emissions of GHG, aerosols, and black carbon from biomass burning.

Seiler and Crutzen (1980) published the first estimation of total burned areas and the amount of biomass burned according to diverse sources in tropical, temperate, and boreal regions. About 80% of the area burned globally occurs in the tropics, where fires are widely used for the purposes of (1) deforestation to clear the land for agriculture and ranching, (2) shifting cultivation for sustaining subsistence agriculture, (3) growing fresh grass for ranching in the savannas, (4) energy consumption for heating and cooking and (5) clearing agricultural residues after harvest. Wildfires and prescribed burning dominate in temperate and boreal ecosystems in the United States, Canada, northern Mexico, Russia, and Australia. Since the global population will continue to grow and the major growth will take place in tropical countries, we anticipate increased fire activity, burned areas, and emissions of greenhouse gases, aerosols, and black carbon in the future. Hence, the impact and the contribution of fires to regional, global climate change are expected to intensify in the coming decades.

In order to understand the geographical impact of fire emissions on regional and global climate and air quality in comparison to other sources (e.g., industry, transportation, agriculture, forest), it is essential to characterize the spatial and temporal distribution of fire activity and burned area for estimation of emissions of GHG, aerosols, and black carbon. We must also overcome the challenges inherent with the transient nature of wildland fires, which tend to be of shorter duration and greater variability than other types of emissions sources. Wildland fire occurrence and emissions will vary on hourly, daily, monthly, and yearly timescales depending on diurnal, weather, seasonal, and climate patterns, as well as human activity and vegetation conditions. Hao and Liu (1994) published the first geospatially gridded monthly biomass burning inventory taking account of different land uses in the tropics at a 5° × 5° resolution based on statistics of the United Nations Food and Agriculture Organization and published literature. By deriving the burned area and the aboveground biomass density in different ecosystems, Hao and Liu (1994) estimated the amount of biomass

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burned in tropical Africa is about twice of that in tropical America because of the dominance of savanna fires in Africa. Our ability to provide such information has been greatly enhanced by the expanding availability of satellite based observations of fire activity and burned areas since the late 1990s, as well as efforts to better report and aggregate fire information gathered by ground personnel, helicopters, and aircraft. Here we review the current satellite-derived active fire detection and burned area products as well as modern ground based fire incident reporting systems.

2. Satellite derived burned areas based on active fire detections

Significant progress has been made in the past 12 years in estimating burned areas spatially and temporally, using NASA's MODIS (MODerate Resolution Imaging Spectroradiometer) instruments on the Terra and Aqua satellites and NOAA's Imager instrument on a series of GOES satellites. The Terra satellite was launched on December 18, 1999, and the Aqua satellite was launched on May 4, 2002. Both satellites provide consistent, spatially gridded coverage globally for the same locations four times daily during a period from early 2000 to present. Data from these satellites allow detection of fire locations and mapping of burned areas in near real-time, thus making essential improvements in understanding the spatial and temporal extent of fire activities and emissions from biomass burning globally.

While the official MODIS active fire product (MOD14A1) offering global daily active fire detections at a 1 km resolution became readily available shortly after the satellite launches, developing the MODIS-derived burned areas at a 500 m resolution has proved to be much more challenging. Active fire detections characterize thermal anomalies relative to the adjacent pixels during the 10-min satellite overpass time. Burned areas characterize the propagation of fires between the satellite overpass intervals. Giglio et al. (2013) developed a method of estimating monthly burned areas at a $1^\circ \times 1^\circ$ resolution globally from 2001 to 2004 derived from active fire detections. The methodology was based on the MODIS-detected active fires, the relationships between the burned areas and active fire observations over selected MODIS scenes, and regression tree analysis over 14 regions worldwide. During this four-year period, on average about 3.4×10^6 km^2 were burned annually globally (Table 1). Approximately two-thirds of the burned areas globally occurred in Africa, 15.5% in Australia, 5.9% in Central Asia, 4.9% in South America, 3.4% in Southeast Asia, 2.6% in boreal Asia, and only 1.1% in boreal and temperate North America. The active fire-derived burned area product served as a preliminary burned area product prior to the development of more accurate burned area products.

3. Satellite detections of burned areas

Satellite-based data on burned areas at a high spatial and temporal resolution globally and regionally have become available only in the last several years because of the difficulty of minimizing false identification of burned scars. The scales of the resolution for the burned area products depend on their applications (Urbanski et al., 2011). For modeling regional air quality, the requirements for the spatial and temporal scales would be less than 25 km and 1 day. For modeling global climate and atmospheric chemistry, the scales would be 0.5°–3° and weeks. The burned area products are being improved continuously by validation with ground observations or high-resolution satellite images (e.g., Landsat images at a 30 m resolution). We will discuss two MODIS-based global burned area products (Roy et al., 2008; Giglio et al., 2010) and a regional burned area product for the western United States (Urbanski et al., 2009, 2011) in the following sections. Additionally, we will discuss other satellite-derived systems such as the Monitoring Trends in Burn Severity product and NOAA's Hazard Mapping System, and provide an overview of the available ground-based reporting systems for wildfires and prescribed fires. The development and improvement of burned area products is an ongoing process, and they should be considered intermediate but not the final burned area products.

3.1. Official NASA MODIS burned area product

Roy et al. (2008) described the official global monthly MODIS 500 m resolution burned area product (MCD45A1) detected by NASA's Terra and Aqua satellites. The mapping of burned areas is based on changes in surface reflectance as a result of fires. The spectral characteristics of burned scars with charcoal and ash are quite different from that of vegetation before being burned. The MCD45A1 burned area product was compared with the MODIS ac-

Table 1
Comparisons of burned areas over 14 regions worldwide in 2001, 2002, 2003, and 2004.

	Burned area (10^4 km^2 yr^{-1})							
	2001		2002		2003		2004	
	Active fire obs[a]	MCD 64A1[b]	Active fire obs[a]	MCD 64A1[b]	Active fire obs[a]	MCD 64A1[b]	Active fire obs[a]	MCD 64A1[b]
Boreal North America	0.4	0.3	2.6	3.2	2.3	2.0	4.0	5.0
Temperate North America	1.4	1.2	1.7	1.4	1.5	1.3	1.2	0.7
Central America	1.8	1.0	2.2	1.0	2.9	1.7	1.8	0.8
NH South America	4.4	2.0	3.6	1.1	4.8	3.3	3.8	3.2
SH South America	12.4	19.4	12.7	21.3	10.8	16.1	13.4	18.7
Europe	2.9	1.1	1.6	0.4	2.6	0.9	1.9	0.5
Middle East	0.6	1.2	0.5	1.0	0.4	0.9	0.4	0.8
NH Africa	153.2	114.4	135.2	126.1	125.5	128.0	129.8	116.4
SH Africa	84.0	117.3	82.4	113.9	79.6	126.6	75.3	127.1
Boreal Asia	6.3	5.8	9.3	8.1	14.5	15.9	4.9	1.6
Central Asia	16.5	15.0	26.7	25.0	17.1	12.8	18.9	15.6
Southeast Asia	10.8	4.5	10.2	7.7	8.4	6.3	16.1	10.7
Equatorial Asia	0.8	0.7	3.4	2.4	1.4	0.8	2.9	1.2
Australia	78.7	88.3	58.9	73.1	24.8	29.0	44.9	60.4
Total	374.2	372.2	351.0	385.7	296.6	345.6	319.3	362.7

[a] Burned areas derived from MODIS detected active fire observations, regional regression trees, and the relationship between burned areas and active fire detections (Giglio et al., 2013).
[b] GFED3 burned areas derived from MODIS detected active fires, change in vegetation analysis, and regional regression trees (Giglio et al., 2010).

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tive fire product (MOD14A1). During the period from July 2001 to June 2002, 3.7×10^6 km^2 were burned globally as estimated by the MCD45A1 and 2.8×10^6 km^2 were burned as estimated by MOD14A1 (Roy et al., 2008). The largest burned areas occurred in Africa, followed by Australia, South America, and Northern Eurasia during this time period for both MCD45A1 and MOD14A1. However, the differences of burned areas varied considerably in different regions and land cover types. The two burned area products are similar over mixed and deciduous broadleaf forest. The MCD45A1 burned areas are less than the MOD14A1 derived burned areas in cropland, evergreen forest, and deciduous needleleaf forest. On the contrary, the MCD45A1 burned areas are higher than the MOD14A1 burned areas over non-forest ecosystems. The different results accentuate the necessity for validation of the active fire product and the burned area product and for improvements of the two products.

3.2. MODIS direct broadcast burned area product (MCD64A1 and DBBAP)

The MODIS direct broadcast (DB) burned area product (MCD64A1) maps daily burned areas at a 500 m spatial resolution globally. The direct broadcast system provides the ground satellite receiving station the capability for receiving, processing, and archiving MODIS data in near real-time during the satellite overpass. The product has been used for (a) estimating global fire emissions by the GFED3 (Global Fire Emissions Database) model (van der Werf et al., 2010), and (b) monitoring the daily fire propagations and burn scars in the United States for operational use by the U.S. Forest Service, Remote Sensing Applications Center. The algorithms of direct broadcast burn area product (DBBAP) are used to map burned areas for the newly launched Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi National Polar-orbiting Partnership (NPP) satellite.

The algorithms of DBBAP were based on the daily MODIS active fire detections, the change in vegetation index, and regional regression trees (Giglio et al., 2009; Giglio et al., 2010), while the mapping of burned areas for MCD45A1 depends mainly on the change in surface reflectance (Section 3.1). The burned areas estimated by DBBAP agree within about 10% with the burned areas derived from selected Landsat images in central Siberia and western United States (Giglio et al., 2009). The overall kappa coefficient (κ) (Congalton and Green, 1999) was 0.82 and an accuracy of 94.8% for western United States, and $\kappa = 0.79$ and an accuracy of 98.4% for central Siberia. The DBBAP burned areas from 1997 to 2008 were also linearly correlated with the fire perimeters assembled by the United States National Interagency Fire Center and the Canadian Interagency Forest Fire Centre (Giglio et al., 2010). As in Giglio et al. (2013), on average about 3.7×10^6 km^2 were burned per year during the four-year period (Table 1). Approximately two-thirds of the average globally burned areas during this time period took place in Africa, followed by Australia 14.5%, 5.8% in South America, 4% in central Asia, and 1.9% in the boreal region of Asia. The total burned areas published by the two methods of Giglio et al. (2013) and Giglio et al. (2010) were agreeable within 7.6% for the 4 years, but the burned areas in each region can vary substantially. The MCD64A1 estimated burned areas were about 39% to 70% higher than active fire-derived burned areas in southern hemispheric Africa and America during this period.

The MCD64A1 burned areas for the GFED4 product were recently updated to include (1) the monthly dataset at a 0.25° resolution from mid-1995 to present, and (2) the daily burned area dataset from August 2000 to present (Giglio et al., 2013). The burned areas before the MODIS period were derived from the active fire detections by the sensors of Tropical Rainfall Measuring Mission (TRMM) and a series of the Along-Track Scanning Radiometers (ATSR). The long time series (12 or 15 years) of burned areas allows for studying the trends of biomass burning in various regions globally. During this time period, the area burned has decreased in Africa in the Northern Hemisphere and Australia and has increased in Africa in the Southern Hemisphere and Southeast Asia.

3.3. MODIS direct broadcast burn area product and its uncertainty for western United States

A different approach of burned area algorithms was developed for the direct broadcast system to map burned areas in near real-time over most of the United States (Urbanski et al., 2009; 2011). The product was developed to map burned areas and estimate fire emissions in near real-time for air quality forecasting by the Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (FiSL). The methodology is quite different from the approaches of MCD45A1 and MCD64A1. The mapping of burned areas was based on the active fire detections, the surface reflectance in a single MODIS image, and a set of algorithms to remove false alarms (e.g., water, cloud shadow). The active fire detections were only used to identify valid clusters of burned area detections but were not used for mapping the actual burned areas. This product uses a single satellite image to shorten the data processing time for air quality forecasting, as both MCD45A1 and MCD64A1 require at least two satellite images to compare the detection change of surface reflectance or vegetation index.

The annual burned areas over the western United States varied considerably from 2003 to 2008, ranging from 3.6×10^3 km^2 in 2004 to 1.9×10^4 km^2 in 2007 (Urbanski et al., 2011). About two-thirds of the areas burned during this time period occurred in four states: California (18.3%), Idaho (18.3%), Nevada (15.8%), and Montana (11.7%). However, the burned areas in each state have been shown to differ by orders of magnitude for different years. For instance, only 8.2×10^2 km^2 were burned in California in 2005, but 3.5×10^3 km^2 were burned in 2007. In Idaho, 6.1 $\times 10^3$ km^2 were burned in 2007 and only 1.1×10^2 km^2 were burned in 2004.

Considerable efforts were made to validate the burned area algorithms for the Forest Service direct broadcast system (Urbanski et al., 2009; 2011). The FiSL MODIS-DB active fire detections for the western United States during the period of 2006–2007 were compared with 966 fire incident perimeters. The algorithms detected 87% of the fires larger than 4 km^2, and 93% of the fires larger than 10 km^2. The detection rate is different for different vegetation types, 100% for conifer forest fires, 75% for grassland fires, and 70% for shrubland fires greater than 2 km^2. Fires in conifer forest often have longer duration and are easier to detect than grassland or shrubland fires. The burned area algorithms were validated by comparison with 142 Burned Area Reflectance Classification (BARC) maps during the same time period. The BARC maps were produced based on high-resolution Landsat satellite images (30 m resolution). In addition, the uncertainty of burned area algorithms was quantified by using the geospatial dataset of burn severity of the Monitoring Trends in Burn Severity (MTBS) project (Section 3.4.2) (Urbanski et al., 2011). The MTBS project consistently maps burn severity and fire perimeters larger than 4.04 km^2 over the United States (http://www.mtbs.gov/). The burn severity at a 30 m resolution in MTBS was classified to five different categories based on Landsat TM/ETM images. The burned areas over the western United States mapped by the FiSL MODIS-DB algorithms are highly accurate with an uncertainty of annual burned areas to be 2–4% from the year 2003 to 2008. Very limited information is available on the uncertainty of burned areas over the eastern United States. Prescribed fires dominate the eastern United States. These understory vegetation fires are smaller, have shorter duration, and are harder to detect compared to the wildland fires in the West.

3.4. Other satellite-derived systems

In addition to the above MODIS-derived burned area products, other satellite-derived fire reporting systems include NOAA's Hazard Mapping System (HMS), as well as the retrospective USFS/USGS Monitoring Trends in Burn Severity product.

3.4.1. Hazard Mapping System

The Hazard Mapping System (HMS) (Ruminski et al., 2008) is an operational platform developed and used by NOAA's Satellite Analysis Branch (SAB) of the Satellite Products and Services Division. The HMS combines shortwave infrared and visible imagery and automated fire detections from algorithms from both polar (e.g., MODIS) and geostationary (e.g., GOES) satellites (7 satellites in total) and allows for manual quality control, whereby analysts can delete suspected false detects and insert additional fires that the algorithms have not detected. The system includes a layer which shows the locations of known false detects, such as the U.S. Steel tower in Pittsburgh. Numerous other false detects are removed due to the misidentification of clouds or ground features. Additionally, NOAA SAB analysts examine animated GOES visible imagery to look for smoke plumes that have little or no hotspot in infrared imagery and, where possible, will track back the smoke plume to a source location and manually add the fire detection as needed. The HMS fire detection products are updated multiple times per day and used in a number of real-time air quality prediction products including NOAA's operational smoke forecast product. Zhang et al. (2011) have shown that the combination of satellite products (GOES + AVHRR + MODIS) as used in HMS improves not only detection but the ability to correctly represent burned area.

3.4.2. Monitoring trends in burn severity

The MTBS product (Eidenshink et al., 2007) is jointly produced by the U.S. Forest Service and U.S. Geological Survey and released by the USFS Remote Sensing Applications Center. The MTBS is the most comprehensive retrospective product monitoring fire activity and burn severity larger than 4 km^2 west of the Mississippi River and over 2 km^2 east of the Mississippi River in the continental United States. MTBS is designed to consistently map the burn severity and perimeters of fires across all lands (not limited to wildlands). MTBS uses pre- and post-burn data from the USGS Landsat Thematic Mapper (30 m resolution) to produce polygons of fire areas that contain gridded 30 m burn severity data. MTBS data are currently available from 1984 to 2010, with additional years being added 18 months to 2 years after their completion.

Analysis of MTBS data from 1984 to 2010 showed that, despite the fluctuated inter-annual variability, the overall trends of the number of fires and total burned areas over the continental United States increased during this period (Finco et al., 2012). The number of fires and the burned area increased slightly in the Eastern Great Basin and only the burned area had a small increase in Southern California. However, the total burned area and the total number of fires in the Pacific Northwest and Pacific Southwest did not have apparent trends from 1984 to 2005 (MTBS, 2008). MTBS dataset was also used in producing fire emissions inventories as part of EPA's 2008 National Emissions Inventory (Raffuse et al., 2012).

4. Ground-based fire reporting systems

Ground-based systems that collect and report information on wildland fire activities vary considerably throughout the country. Reporting systems are typically tied to specific states, land ownerships, and/or fire types, resulting in a patchwork of available fire information. Additionally, as the reporting systems have developed to fulfill specific administrative functions, the manner in which the systems are used, including the timeline and accuracy of the data available within them, varies considerably. Very few reporting systems have been developed to support wildland fire emissions calculations or are aimed at all the types of fire (wildfire, prescribed fire, and agricultural burning).

The most spatially complete systems for ground-based reporting of fire are related to wildfires and fire suppression efforts. In the United States, wildfire suppression efforts are coordinated through the multi-agency National Interagency Coordination Center (NICC, http://nifc.gov/nicc), which oversees 11 regional Geographic Area Coordination Centers. NICC and the National Wildfire Coordinating Group's (http://nwcg.gov) National Fire and Aviation Management Web Applications (FAMWEB, http://fam.nwcg.gov/fam-web) group maintains the wildfire report database consisting of Incident Command System (ICS) 209 reports that are generally done on a daily basis for active wildfire incidents in order to support prioritization of wildfire suppression efforts and allocation of fire-fighting resources. The ICS-209 reports cannot be used for real-time applications because they may be delayed by a few days before posting and can have location and other data entry errors, but this data often is a primary source of fire sizes and other fire related data (e.g., the fire name and incident type) not widely available elsewhere. The Geospatial Multi-Agency Coordination Group (GeoMAC) also maintains a geospatial database of active fire areas based on incident intelligence sources, GPS data from ground personnel, infrared imagery from aircraft, and satellite data. These perimeter data are often used in both decision-making and public briefings on wildfires, as well as later studies of fire emissions and air quality. Some of these geospatial data can also be found in the new multi-agency Wildland Fire Decision Support System (WFDSS) application that is being used as a primary decision support and documentation tool by federal land management agencies. Other wildfire incident data can be found with the various federal and state agencies, but the above databases are the primary ones for fire area information.

For prescribed fire on federal land, each federal land management agency maintains its own database for tracking hazardous fuels treatments. The Forest Service Activity Tracking System (FACTS) database was developed by the U.S. Forest Service. The Department of Interior's primary system is the National Fire Plan Operations and Reporting System (NFPORS), but individual agencies (notably the Fish and Wildlife Service) also use their own systems. It is difficult to track such activity at the federal level, because different regions in an agency may utilize the databases in different ways, supplying different data quality levels to the system on different timelines, and some federal agencies manage prescribed burn activities on non-federal land through agreements with private and state landholders.

For prescribed fire on non-federal land, tracking systems vary widely in both coverage and use across the country. The Pacific Northwest region is considered a model for tracking prescribed burning, in part because state air quality regulations in this region have resulted in state permitting systems (e.g., in Washington, Oregon, Montana, and Idaho) for prescribed burning that track burning even on private land. In other states, prescribed fire information is notably lacking (e.g., Nevada), sometimes due to state "right-to-burn" laws that inhibit data collection (e.g., Colorado for agricultural burning). Because the large amount of prescribed burning in the Southeast and the level of poor regional air quality often impacting this region, prescribed fire tracking systems in this region are particularly important. Federal land is limited in the Southeast, but several states in this region have tracked prescribed burning (e.g., North Carolina, Georgia, and Florida). However, there

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are not prescribed fire tracking systems currently implemented in the Southeast or elsewhere that are effective in capturing the full range of burning activities.

The importance of tracking small wildfires and prescribed burns points to the necessity to utilize the available information from ground-based systems that track these fires. It has resulted in the recent development of the Forest Service SmartFire v2 platform for reconciling fire information. SmartFire v2 is a modular framework that integrates, associates, and reconciles fire information from a wide range of satellite systems and ground-based systems using metrics that reflect the uncertainties and errors known to exist within each reporting system. SmartFire v2 was recently used as the primary basis for producing the wildland fire component of the EPA National Emissions Inventory (Raffuse et al., 2012). In the contiguous United States using such methods shows the area of prescribed burning as exceeding that of wildfire (Larkin et al., this issue).

5. Reporting differences

It is important to note that the different systems discussed here report in different ways. The differences include:

- the actual reported burned areas (e.g., cumulative fire size to date, burn severity, past burned area, current burning area, simply hotspot latitude and longitude);
- the uncertainty associated with the reported data (e.g., the grid resolution of the system and the inherent errors, uncertainties of the system);
- the timelines of data availability (e.g., near-real time reports of hotspot detection, analyses taken months to years after the fact);
- the timing of the data (e.g., satellite overpass times in different parts of the country);
- the coverage of the data (e.g., on satellite paths, detection capabilities in different fuel types, and, for ground-based systems, administrative constraints such as land ownership and/or fire type);
- the time resolution of the data (e.g., daily or hourly fire growth, final fire size); and
- the consistency of the data due to cloud and smoke obscuring satellite detections or regional administrative differences in the ground reporting of data.

These differences result in varying fire products that are developed for different applications. Overall, for determination of the location and area of wildfires, satellite burn scar mapping systems have proven to be successful. However, such systems are less capable of mapping agricultural fires and prescribed burns, and, over CONUS where they are available, geostationary satellite systems are able to detect more prescribed burns and agricultural burns than burn scars of polar orbiting systems. In some parts of the country with particularly good ground-based prescribed fire and agricultural fire tracking databases, such regional reporting systems may provide the most accurate information.

6. Knowledge gaps

Currently there are a number of areas in which our ability to accurately characterize wildland fire is limited:

(1) Although tremendous improvements have been made on the recent burned area products, they are only consistent qualitatively. There are significant discrepancies in the exact distribution of burned areas spatially and temporally. It is crucial to compare the various burned area products in different spatial (500 m, 1 km, 0.5°, 1°) and temporal scales (daily, 8 days, monthly, yearly) over different ecosystems worldwide. The strengths and weakness of each burned area product and its applications should be investigated.

(2) There is a lack of understanding on the major factors affecting the seasonal and interannual variability of burned areas over different ecosystems. The factors can be due to human activity, lightning, weather, vegetation conditions, and changing climate.

(3) It is essential to study the impact of future climate on the burned areas in order to understand the future interactions among climate, landscape, fire dynamics, fire emissions, and air quality.

(4) More integrated and validated prescribed fire and agricultural burning datasets are needed to support emissions calculations and address key uncertainties present in current reporting systems and emission inventories.

(5) A standard methodology for integrating all the available fire information into a consistent and accurate data stream is needed to ensure the best fire emission inventories. This methodology has to be developed with an understanding of the range of uses of fire emission inventories-particularly the range of timelines-from near real-time information for air quality predictions to retrospective fully validated information for regulatory modeling.

7. Conclusions

Several important progresses have emerged after a decade of research on the spatial and temporal extent of wildland fires.

Satellite based burned area products have been developed with different spatial and temporal scales globally or over specific regions, depending on the applications. The official NASA MODIS burned area product and MODIS direct broadcast burned area product were developed for modeling global atmospheric chemistry and climate. The MODIS direct broadcast burn area product for western United States was developed for studying regional air quality and climate. The recent satellite-derived burned area products have been improved substantially by comparing them with the high-resolution Landsat images to validate the MODIS-derived burned areas. The latest development of burned area products also have tended to focus on improving spatial and temporal resolution, which is of benefit in studying air quality, global atmospheric chemistry, and climate.

Understanding uncertainty is crucial in determining how fire products can be used for various applications. Comparisons between satellite systems, ground systems, and burn scars are an active area of research that will likely help improve wildland fire information products and fire emissions inventories in the future. Quantification of these comparisons is usually carried out using advanced statistics.

Current satellite fire detection and burned area products will certainly change in the future as current satellite missions reach the end of mission lifecycles and newer missions (e.g., NOAA GOES-R, Joint Polar Satellite System) and instruments are launched. In some cases these changes will result in improved fire detection and burn scar detection products, but other satellite sensors are expected to become less appropriate for fire use. These issues are in flux as next-generation satellite parameters are being finalized. These changes present both a large challenge and potential opportunity for improving our ability to detect and measure wildland fire in the future.

Prescribed fires are a significant contributor to wildland fires. Prescribed fires tend to be smaller in size and occur over a shorter duration than wildfires, making them harder to detect from satel-

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lites as compared with wildfires. They can also occur as understory burns that are harder to detect. For certain regions (such as the U.S. Southeast), prescribed burning is a significant air quality concern. Ground-based reporting systems, which have significant quality control and timeline issues, can still provide valuable information particularly on prescribed fires. Some systems, such as the USFS SmartFire v2 fire information platform, have been developed specifically to help reconcile both satellite and ground-based reporting system information.

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