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Quantifying burned area for North American forests: Implications for direct reduction of carbon stocks

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[1] A synthesis was carried out to analyze information available to quantify fire activity and burned area across North America, including a comparison of different data sources and an assessment of how variations in burned area estimate impact carbon emissions from fires. Data sets maintained by fire management agencies provide the longest record of burned area information. Canada and Alaska have the most well developed data sets consisting of the perimeters of large fires (>200 ha) going back to 1959 and 1950, respectively. A similar data set back to 1980 exists for the Conterminous U.S., but contains data only from federal land management agencies. During the early half of the 20th century, average burned area across North America ranged between 10 and 20×10^6 ha yr^{-1}, largely because of frequent surface fires in the southeastern U.S. Over the past two decades, an average of 5×10^6 ha yr^{-1} has burned. Moderate-resolution (500–1000 m) satellite burned area products information products appear to either underestimate burned area (GFED3 and MCD45A1) or significantly overestimate burned area (L3JRC and GLOBCARBON). Of all the satellite data products, the GFED3 data set provides the most consistent source of burned area when compared to fire management data. Because they do not suitably reflect actual fire activity, the L3JRC and GLOBCARBON burned area data sets are not suitable for use in carbon cycle studies in North America. The MCD45A1 data set appears to map a higher fraction of burned area in low biomass areas compared to the GFED3 data set.

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1. Introduction

[2] Fire is present to some degree in all North America's terrestrial ecosystems, where its occurrence, frequency, and extent are driven by a combination of the type, amount, and moisture content of fuels available for burning, the presence of an ignition source, and weather conditions at the time of burning. Like other disturbances, fire is important in regulating North America's terrestrial carbon budget of forest ecosystems (and other ecosystems as well) [see, e.g., *Barger et al.*, 2011; *Grosse et al.*, 2011]. Its effects are like those from other disturbances because they all cause major changes to the biotic and abiotic characteristics of an ecosystem, which in turn, alter carbon fluxes resulting from photosynthesis and respiration. The magnitude of changes caused by different disturbances is likely to vary because each disturbance affects different components of the biotic and abiotic environment, and in addition, there can be pronounced differences in severity. The effects of forest disturbances on carbon cycling at decadal scales are often readily recognized and modeled because ecosystems experience systematic changes to species composition, net plant growth, and heterotrophic respiration that can be observed and measured [*Amiro et al.*, 2010; *Harmon et al.*, 2011].

[3] Studies that investigate the more recent impacts of fires in the U.S. and Canada are facilitated by fire management records that provide documentation of where and when fires have occurred over the past 50 to 60 years [*Kasischke et al.*, 2002; *Stocks et al.*, 2002; *Stephens*, 2005]. As ecosystems age, the impacts of older fires on carbon cycling at landscape scales become more difficult to systematically study because of the lack of reliable data on where fires actually occurred. In addition, plant community dynamics become more complicated as stands approach maturity, making consistent observations on the existence of fire legacy effects difficult

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to detect at individual sites (except where scars are present and can be documented through analysis of tree rings).

[4] The impacts of fires on carbon cycling are different from other disturbances because combustion processes produce emissions of a number of carbon-based trace gases (primarily CO_2, CO, and CH_4) and create black carbon [*Andreae and Merlet*, 2001]. As such, fire is one of only five processes that can result in a direct exchange of carbon-based greenhouse gases between the atmosphere and the land surface (the other four being photosynthesis, autotrophic respiration, heterotrophic respiration, and emission of complex hydrocarbons by plants through biological pathways). From a carbon accounting perspective, fires result in an instantaneous reduction of carbon present in different pools (live biomass, dead woody debris, litter, organic soil, etc.). Thus, information requirements for assessing the impacts of fire on carbon cycling are more complex, requiring information on fire severity in terms of the amounts of biomass directly consumed during a fire. This information is often provided directly (e.g., mapped fire severity) or indirectly (e.g., the timing of fire which is then related to weather conditions at the time of fire which is used to estimate fuel moisture and consumption).

[5] Regardless of the overall consequences, biogeochemical cycling and emission models require specific information to account for the influences of fire on the carbon cycle of North America's terrestrial ecosystems. At a minimum, this information includes the location, area and timing of fire events and/or the observed or expected fire free interval for a specific vegetation type or ecosystem and the range in fire severity that they experience. For modeling the impacts of fire severity on carbon cycling at continental scales, additional information requirements include: (a) how much live and dead biomass is directly combusted during a fire event; (b) the rates of mortality as a function of plant species; and (c) the impacts on the biotic and abiotic components of the ecosystem that will influence post-fire succession, regrowth, heterotrophic respiration, and export of soil carbon.

[6] As part of the North American Carbon Program (NACP), we present here a synthesis of research on approaches to estimate burned area, focusing on five questions:

[7] 1. What are the sources for burned area data and what are the differences between these data sets?

[8] 2. What are the sources of uncertainty in longer-term burned area data sets?

[9] 3. What are the approaches to modeling burned area and what are their uncertainties?

[10] 4. How do the estimates of burned area derived from satellite remote sensing data differ from estimates from fire management records at a regional scale?

[11] 5. How do the differences in the burned area data sets contribute to variations in estimates of carbon consumed during wildland fires?

2. Methods

2.1. Fire Data Products for North America

[12] There are four sources of information on burned area that can be used for modeling the impacts of fire on carbon cycling. At very-long time scales (centuries to millennia), paleo records from analyses of tree rings and lake bottom sediments provide information on the frequency of fires at regional scales. Fire management records provide burned area information going back to the early 20th century. For the past several decades, information on burned area, fire frequency, seasonal timing of fire activity, and fire severity is available in products generated from processing data collected by satellite remote sensors. Finally, for predicting future burned area, models have been developed at both regional and global scales. For this synthesis, we analyzed data sets from land management agencies, satellite remote sensing, and modeling.

2.1.1. Fire Management Records

[13] Fire management data provide the longest record of burned area and other statistics available for modeling the impacts of fire on carbon cycling in North America. Over the last half of the 20th century, burned area on a regional scale has been estimated by summing the areas calculated for the individual fire events. For the earlier years of the 20th century, there is no clear documentation on how burned area estimates were derived. Based on the large burned areas reported and the nature of the technology available to observe and map fires, we feel that in many cases, estimates of burned area produced in the first half of the 20th century were based on the best guesses of fire managers using seasonal fire-weather conditions and direct observations of the level of fire activity as guidelines (see section 2.2).

[14] The longest (over time) continuous records of burned area are seasonal compilations of burned area for specific countries, states, or provinces/territories. For many North American regions, fire records exist for individual fire events, which contain maps of the fire perimeter, the estimated area within the fire perimeter, the ignition source for the fire (human, lightning, etc.), the location where the fire started, the start or discovery date, and the end date for the fire. The end date for a fire event may be the day fire activity actually ceased, or in many cases, the date that fire managers declared the fire out for administrative purposes (which can be weeks, even months after a fire had actually stopped burning). For many regions, the data from individual fire events have been compiled into spreadsheets that can be readily analyzed by interested parties.

[15] For Alaska, Canada, and the conterminous U.S., perimeters from larger fires (>100 to 400 ha) have been digitized and are available in files that can be imported into a geographic information system (GIS). These data sets allow for detailed analyses of the characteristics of fire events, and can easily be integrated with other geospatial data used in analysis of the impacts of fire on carbon cycling, especially the estimation of emissions. Because most area burned in forest fires in Alaska, Canada, and the U.S. occur in large fire events, these fire perimeter data sets are the most useful for studying the impacts of specific fire events on carbon cycling. Use of some these fire perimeter data sets may be limited by the fact that they do not contain all of the events that occur in a specific region, only those from specific land management agencies. These limitations are further discussed in the following sections.

[16] Burned areas for individual large fire events are typically determined by estimating the area within the perimeter of the event. Measuring burned area is dependent on the ability to map the perimeter of the fire event, and in some cases, to map the larger islands of unburned area within the perimeter. In most cases, fire management agencies are

primarily interested in the area being impacted by fire to aid in monitoring and suppression efforts; therefore, very little effort is devoted toward discriminating and mapping of burned and unburned areas within perimeters. As a result, statistics reported by land management agencies do not actually represent burned area, but rather the area that was impacted by specific fire event based on its perimeter.

[17] None of the available data sets from fire management agencies separates burned area as a function of vegetation type. Thus, determining burned area for forests requires the development of an approach to stratify the burned area information based on the vegetation cover where the fires occurred. This can be accomplished by either: (a) assuming that all vegetation types in a region that burns have some designated probability of burning; or (b) integrating a perimeter map with a vegetation cover map within a GIS for a specific fire event. The fire management data available for specific regions of North America are summarized below.

2.1.1.1. Mexico

[18] Mexico started compiling burned area on a national scale in recent years. Burned area data are available on a state level since 1990, and at a municipality level since 2005. Information for individual fire events is available on a limited basis.

2.1.1.2. Canada

[19] In Canada, fire management data are collected and archived primarily by provinces and territories, except for national parks, where data are compiled by Parks Canada. Currently, the Canadian Interagency Forest Fire Centre (CIFFC) keeps track of all active fire events, coordinates fire management activities, and compiles annual statistics on burned area. The burned area estimates for each province, territory, and Parks Canada are summarized in an annual report (http://www.ciffc.ca).

[20] Seasonal area burned estimates have been compiled at a national level for Canada back to 1918 [*van Wagner*, 1988]; however, this longer-term data set under-estimates burned area in earlier years because most provinces did not monitor fires that occurred in remote, northern regions, and the Northwest Territories and Newfoundland did not start monitoring fires until the 1950s and 1960s [*Stocks et al.*, 2002]. Satellite mapping of fires began in the early 1970s in these more remote regions to augment ground- and aerial-based surveys [*Epp and Lanoville*, 1996].

[21] Development of a more comprehensive record of large fires in Canada began in 1989 in an effort to map and study trends in burn area [*Stocks et al.*, 2002]. The Canadian Large Fire Database (LFDB) (completed initially in ca.1997) was developed as a database of fire locations (points) that includes start date, start location, cause, and size (see http://cwfis.cfs.nrcan.gc.ca/en_CA/lfdb). The LFDB includes all fires greater than 200 ha, which represents approximately 97% of all area burned [*Stocks et al.*, 2002]. Fires in this data set cover 1959 to 2008 (as of publication of this paper) compiled annually from records provided by Canadian Provinces and Territories. The Provincial records were developed through several methods, including compilation of individual wildfire reports, digitized GIS-based maps of fires from reports, and records based on other provincial resources, such as reconnaissance aerial mapping and some satellite-derived information. More recently, the National Fire Database (NFDB) was developed, which includes both fire locations (points representing the geocentroid of fires) and perimeters (polygon representations of the fire extent when available), in addition to the attributes available in the LFDB (J. Little, personal communication, 2010).

2.1.1.3. Conterminous U.S.

[22] For the U.S., the first attempts to quantify burned area occurred in 1880 when Professor Charles Sargent of Harvard distributed a circular to every town in America to determine the sources for and amount of fire that occurred in different regions [*Sargent*, 1884]. Based on this survey, Sargent estimated that 4,159,542 ha of forest burned in the conterminous U.S. in 1880.

[23] The systematic compilation of burned area estimates for the U.S. was initiated in 1916 by the U.S. Forest Service [*Houghton et al.*, 2000]. Because the manner in which these data were reported before 1926 is in not clear, most researchers use the burned information from 1926 onwards. Even so, there is no clear record or documentation on the methods used to estimate the large burned areas that occurred in the conterminous U.S. in the 1920s through the 1950s. The burned area by state database exists through 1990. State-by-state summaries of burned area are available from the National Interagency Fire Center (NIFC) for the years 2000–2009 (http://www.predictiveservices.nifc.gov/intelligence/intelligence.htm). In 1998, NIFC began to keep separate records of seasonal area burned for wildland fires and prescribed fires.

[24] The compilation of detailed fire statistics for the Conterminous U.S. is complicated by the fact that a number of state and federal agencies have jurisdiction over management of the fire events that occur on the lands they control, and there has not been a concerted effort to compile fire statistics into a unified database. Rather, databases have been compiled by individual agencies (notably the U.S. Forest Service [*Stephens*, 2005]), but not all.

[25] Some efforts have produced databases from multiple agencies. The most comprehensive data set for modeling purposes is the U.S. Federal Fire Occurrence Data, which contains fire location information for large fire events (>ca. 200 ha) for the years 1980–2008 (http://wildfire.cr.usgs.gov/firehistory/data.html). A gridded (1 by 1 degree) version of this database has been generated by *Westerling et al.* [2003] (http://ulmo.ucmerced.edu/w_FireData.html). These databases contain information on fires on lands managed by the U.S. Forest Service, National Park Service, Bureau of Indian Affairs, Bureau of Land Management, and Fish and Wildlife Service), and thus do not represent total burned area in a region.

2.1.1.4. Alaska

[26] Like the conterminous U.S., fire events in Alaska are managed by the agencies responsible for the lands where the burning occurs. Unlike the conterminous U.S., records for each fire event are kept by those agencies and also by the Alaska Fire Service (AFS) of the Bureau of Land Management. Burned areas for individual events are estimated and information provided on a daily basis in reports generated by the Alaska Interagency Coordination Center (http://blm.fire.ak.gov). Annual summary reports of fire activity are also issued by ASF. In the early 1990s, AFS created a spreadsheet with information on each fire event. In the mid-1990s, a group of university researchers obtained copies of the perimeters of all fire events >400 ha dating back to 1950 and digitized them to create a large fire perimeter database [*Kasischke et al.*,

2002]. AFS eventually took over the management of this fire perimeter database in the mid to late 1990s, and began to add additional perimeters from fires >100 ha, as well as fire perimeters from the 1940s where available. The Alaskan Large Fire Database (ALFDB) is updated by AFS annually, and contains fire perimeters and all pertinent information for each fire event, including data for all fires smaller >100 ha from the mid-1990s onward (see http://blm.fire.ak.gov).

2.1.2. Satellite Information Products

[27] Observations of ongoing fire activity and assessment of burned area became one of the earliest land surface monitoring applications for information derived from satellite remote sensors [*Flannigan and Vonder Haar*, 1986, *Kasischke et al.*, 1993; *Chuvieco and Martin*, 1994]. Over the nearly 40 years of satellite observations, an extensive suite of algorithms and fire products have been developed from a large number of passive and active land surface remote sensing systems. Despite the volume of developed algorithms and products, only a few provide to the means to obtain repeatable, multiyear observations of fire activity across the full extent of Canada, Mexico, the Conterminous U.S. and Alaska.

2.1.2.1. Moderate-Resolution Sensor Burned Area

[28] The growing recognition of fire as an important source of trace gas emissions as well as an important driver of the terrestrial carbon cycle provided the impetus for the development of several different spatially and temporally explicit global burned area data sets through the processing of moderate-resolution (0.5 to 8.0 km pixel size) satellite remote sensing data. While not specifically directed toward the NACP, by their very nature these data sets provide complete coverage of North America dating back to the late 1990s and are therefore highly relevant.

[29] Four global burned area products that are readily available were used in this synthesis, including: 1) the L3JRC burned area product (http://bioval.jrc.ec.europa.eu/products/burnt_areas_L3JRC/GlobalBurntAreas2000-2007.php), 2) the GLOBCARBON burned area product (http://www.geosuccess.net/), 3) the Collection 5 MODIS MCD45A1 burned area product (http://modis-fire.umd.edu/Burned_Area_Products.html), and 4) the Global Fire Emissions Database 3 (GFED3) monthly burned area data product (http://www.falw.vu/~gwerf/GFED/GFED3/emissions/).

[30] The L3JRC data set was produced from 1-km SPOT VEGETATION data and currently spans April 2000 – March 2007 [*Tansey et al.*, 2008]. The GLOBCARBON product was derived from a combination of 1-km SPOT VEGETATION, Along-Track Scanning Radiometer (ATSR-2), and Advanced ATSR 1-km data using a combination of algorithms, and is currently available for the April 1998 – December 2007 time period [*Plummer et al.*, 2006]. The Collection 5 MODIS MCD45A1 burned area product [*Roy et al.*, 2008] was derived from 500-m MODIS imagery and is available from mid-2000 through the present. As with the L3JRC and GLOBCARBON products, burned area in the MODIS MCD45A1 product was mapped on a daily basis. The GFED3 0.5° monthly burned area product, available from July 1996 through the present, is the newest entry in the product suite. GFED3 was produced using a combination of approaches and satellite data from multiple sensors. From mid-2000 onward most of the area burned is mapped directly using 500-m MODIS data and subsequently aggregated spatially and temporally. Prior to mid-2000 (the beginning of the MODIS era) burned area is estimated indirectly using active fire observations acquired with a combination of older spaceborne sensors, primarily the ATSR [*Giglio et al.*, 2010].

[31] Efforts to extend the satellite record of burned area earlier than 2000 exploit the long-term data acquired by the Advanced Very High Resolution Radiometer (AVHRR) series of sensors. Because no AVHHR based-products were available for the 2000s for comparison to other satellite information products across all of North America, they were not included in this synthesis. A detailed discussion of AVHRR fire products is presented in the auxiliary material.[1]

2.1.2.2. Medium-Resolution Sensor Burned Area

[32] Numerous algorithms have been proposed for obtaining burned area estimates from medium-resolution (10–100 m pixel size) satellite remote sensing data: Landsat Multispectral Scanner (MSS) [*Salvador et al.*, 2000], Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) [*Michalek et al.*, 2000; *Koutsias and Karteris*, 1998; *Smith et al.*, 2007], Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) [*Polychronaki and Gitas*, 2010], SPOT 5 [*Norton et al.*, 2009], and ERS Synthetic Aperture Radar (SAR) [*Bourgeau-Chavez et al.*, 1997, 2002; *Siegert and Ruecker*, 2000]. The majority of these data sets were developed for monitoring the extent of fire occurrence at regional scales or to validate moderate-resolution burned area products. The only data set that meets the criteria for at least sub-continental coverage, multiyear assessments, and broad availability is being produced by the Monitoring Trends in Burn Severity (MTBS) project [*Eidenshink et al.*, 2007].

[33] The MTBS data set presents satellite derived burned severity assessments within the fire perimeters recorded by fire management agencies. The majority of fire management records are compiled within the Incident Command System (ICS) 209 database maintained by the National Interagency Fire Center (http://www.nifc.gov); however, some fire perimeters are obtained from State agencies in cases when it is not clear if a specific fire event is included in ICS 209 archive [*Eidenshink et al.*, 2007]. Fire management records were reprocessed within the MTBS project to remove duplicate records, adjust or correct spatial information, and add attributive information detailing incident name, reporting agency, start date of the fire event, geographic coordinates and the corresponding Landsat World Reference System (WRS-2) path and row. In its completed form, the fire history MTBS data set will contain spatially explicit record of fires over 202 ha (500 acres) in the eastern part of the continental U.S., and 404 ha (1000 acres) and greater in the western U.S. and Alaska from 1984 to 2010.

[34] Although the primary focus of the MTBS data set is on providing burn severity information for a national scale analysis of multiyear trends [*Eidenshink et al.*, 2007], this data set also provides an improved estimate of burned area by 1) generating more precise fire perimeters based on satellite observations; and 2) providing differentiation between burned and unburned area within fire perimeters. New fire perimeters, digitized manually on-screen, are based on the

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011JG001707.

change in surface parameters after fire occurrence reflected in the differenced Normalized Burn Ratio (dNBR) index. Burn severity mapping within these fire perimeters allows for additional differentiation between burned and unburned area and helps eliminate unburned islands from burned area estimates. The total amount of unburned area can be as much as 10 to 25% of the area within fire perimeters; however, this value may vary under different burning conditions.

2.1.2.3. Seasonal Fire Trends

[35] Applications of satellite-based fire monitoring and mapping extends beyond observation of fire occurrence obtained from the active fire products and mapping of fire impacts on landscape from burned area products. The MODIS active fire product [*Giglio et al.*, 2003] provides daily observations of fire activity globally. The MODIS instrument, positioned on two polar-orbiting satellites Terra (launched in 1999) and Aqua (launched in 2002), has a minimum of four daily overpasses (one ascending and one descending overpass for each of the satellites daily) with the number of daily observations increasing with increase in latitudes as the orbital swaths begin to overlap.

[36] The publicly available, multiyear record of fire activity spurred the development of analyses evaluating fire occurrence seasonality at continental and global scales. *Giglio et al.* [2006] provided the first global analysis of seasonality of fire occurrence using the MODIS active fire product assessing annual periodicity, seasonality (including season length and peak month), diurnal fire cycle, and burning intensity across all biomes. Increased frequency of MODIS of observations toward higher northern latitudes allows for development of more complex methods of observation of fire dynamics. A fire spread reconstruction approach developed for boreal biomes clusters MODIS fire detections in space and time to identify contiguous fire events, their approximate point of ignition, duration of individual events and mean fire spread rate between successive observations [*Loboda and Csiszar*, 2007].

[37] Tracking the development of fire events and providing general characterization of fire regimes is also possible from using the global MODIS burned area products (described above). Both the MCD45A1 burned area product and the GFED3 monthly burned area data set retain the potential date of burning for each pixel mapped as burned. However, due to smoke and cloud obscuration of the surface, the information derived from these data may differ from the actual date of burning [*Giglio et al.*, 2008]. New approaches to fire emissions modeling use daily MODIS fire detections to improve estimates of date of fire occurrence within the MODIS burned area products or to detail fire progression within the temporally uniform MTBS fire perimeters [*French et al.*, 2011]. Using MODIS fire detections within fire emissions modeling framework also provides additional information about the burning process in terms of location and intensity of residual burning after the initial fire front progression.

[38] Although MODIS active fire detections are the most common data source currently used for characterization of fire timing, other satellite-based approaches can be implemented to improve evaluation of wildland fire dynamics across large regions. *Roberts et al.* [2009] used Spinning Enhanced Visible and Infrared Imager (SEVIRI) on Meteosat-8 (a European geostationary satellite) to characterize annual and diurnal dynamics of biomass burning in Africa. The U.S. Geostationary Operational Environmental Satellite (GOES) also provides observations of fire occurrence across the entire North America from its Automated Biomass Burning Algorithm (ABBA) product [*Prins et al.*, 2001]. However, in the current geostationary systems the nearly continuous observations of ongoing fire activity (15 and 30 min repeat cycle for Meteosat and GOES, respectively) are counterweighted by lower resolution (9 km^2 and 16 km^2 for Meteosat and GOES, respectively) which adds considerably to an uncertainty in the actual fire location within the pixel compared to the 1 km^2 MODIS detections [*Soja et al.*, 2009], especially at higher latitudes where resolution is degraded by increasing distance to the satellites.

2.1.2.4. Assessment of Fire Severity/Impacts

[39] Satellite observations are also now routinely used to evaluate the intensity or severity of specific fire events and subsequent burn severity. There are two major approaches to deriving this information from remotely sensed data sources. The first deals with observations of changes in surface reflectance characteristics post-fire and inferring the total impact from the fire event on the specific landscape (burn severity mapping). The second focuses on the energy released from ongoing burning and relates it to fire intensity and fuel consumption (fire radiative power/energy).

[40] Attempts at relating fire-induced changes in surface reflectance to the severity of fire impacts and their influence on burn site recovery started in the 1990s [*White et al.*, 1996], and a variety of approaches have been developed (for a review, see *French et al.* [2008]). The most common index being used to assess burn severity is the differenced Normalized Burn Ratio (dNBR) which is based on changes in spectral response in near-infrared (NIR) and short-wave infrared (SWIR) (~2.1 μm) band between pre-burn and post-burn Landsat TM and ETM+ imagery. By the mid 2000s it was accepted as the operational approach to burn severity mapping within the MTBS project and is now routinely generated for all large fire events across the U.S. [*Eidenshink et al.*, 2007]. For the MTBS-generated products, the changes in spectral response of fire impacted areas are related to burn severity through a field-based assessment of fire impacts on various components of a particular ecosystem combined into a Composite Burn Index (CBI) developed by the National Park Service [*Key and Benson*, 2006]. The relationship between CBI and dNBR has been evaluated across numerous regions of North America using both linear and nonlinear models. There is still much ongoing debate within the fire science and remote sensing communities on the use of dNBR/CBI relationship and other approaches to map fire severity [see *French et al.*, 2008], including the value of using CBI to represent fire severity [*Roy et al.*, 2006; *Kasischke et al.*, 2008].

[41] Fire Radiative Power (FRP) is an instantaneous measurement of energy released from ongoing burning at the time of satellite overpass [*Justice et al.*, 2002]. FRP characterizes fire intensity [*Ichoku et al.*, 2008], which has been shown to be related to fuel consumption [*Freeborn et al.*, 2008]. The MODIS active fire product operationally provides measurements of FRP for each fire detection point for the entire MODIS record. MODIS-based estimates of FRP have been used to estimate global emissions from fires [*Ellicott et al.*,

2009; *Vermote et al.*, 2009]. Present applications of FRP for characterization of fire intensity are limited because of the highly temporally dynamic nature of burning processes which can change rapidly throughout the day and are not captured by instantaneous measurements during satellite overpass. This limitation is resolved by combining multiple FRP measurements into an integrated assessment of Fire Radiative Energy (FRE). One of the approaches to developing FRE is based on merging multiple FRP measurements from polar orbiting platforms with burned area maps [*Boschetti and Roy*, 2009]. A more straightforward approach integrates high frequency FRP measurements from a geostationary platform [*Roberts et al.*, 2009]. Although currently only coarse resolution instruments offer capabilities for continental measurements of FRP/FRE, detailed assessment of FRP for individual fire events is possible using moderate resolution retrievals from ASTER [*Giglio et al.*, 2008]. FRE offers promising results in estimating fuel mass loss and trace gas and aerosol emissions; however, researchers have found that these estimates are influenced considerably by sensor characteristics, viewing angle and fuel types [*Freeborn et al.*, 2008]. To overcome the existing limitations, further improvements to FRP/FRE retrievals may be necessary to account for sub-pixel fire sizes and temperatures [*Eckmann et al.*, 2008].

2.1.3. Modeling Burned Area

[42] To date, there have been relatively few attempts to develop models that predict burned area. The models that have been developed fall into two broad categories: (a) global-scale models that estimate fire frequency based on fuel type, fuel load, seasonal and inter-annual variations in weather, and sources of ignitions; and (b) regional-scale approaches that assume a given spatial distribution of fuel types (and in some cases fuel loads) where the models are developed based on empirical relationships between weather variables and observations of burned areas.

[43] Both *Arora and Boer* [2005] and *Thonicke et al.* [2010] developed approaches to model fire within the framework of dynamic vegetation models. Neither study provides an extensive evaluation of the ability of these approaches to simulate burned area based on comparison to actual observations; however, *Thonicke et al.* [2010] compared predicted fire activity with fire activity observed using MODIS hot spots (which do not provide information on burned area). This comparison showed the predicted fire activity was consistently lower than observed fire activity.

[44] Empirical models of burn severity for different regions of North America have been developed over the past decade. Three of these models were developed using a combination of seasonal weather data and fire weather indices generated by the Canadian Forest Fire Danger Rating System [*Stocks et al.*, 1989]. The approaches used included stepwise linear regressions [*Flannigan et al.*, 2005; *Spracklen et al.*, 2009] or non-parametric models (*Balshi et al.* [2009] and *Kasischke et al.* [2010], based on the results of *Duffy et al.* [2005]). Three of these efforts provided comparisons of model predictions versus burned area from fire management records: *Balshi et al.* [2009] for the North American boreal forest; *Spracklen et al.* [2009] for the western U.S.; and *Kasischke et al.* [2010] for Alaska. These results provided the basis for an evaluation of the model-predicted burned area for this synthesis.

2.2. Impacts of Differences in Burned-Area on Estimating Carbon Consumption by Wildland Fires

[45] One of the primary uses for burned area information is to estimate the amounts of biomass directly consumed by biomass burning, which in turn, is used to estimate trace gases and particulate matter emissions and reduction to standing stocks of carbon. A number of the burned area products discussed in the previous sections have been used to aid in the generation of the emissions/carbon consumption estimates for the North American region or portions of this region [*Amiro et al.*, 2001; *Balshi et al.*, 2007; *French et al.*, 2004; *Hoelzemann et al.*, 2004; *Ito and Penner*, 2004; *Kasischke et al.*, 2005; *Mouillot et al.*, 2006; *Schultz*, 2002; *Spracklen et al.*, 2009; *van der Werf et al.*, 2006, 2010].

[46] Evaluating the role that variations in burned area has in causing differences in emissions/carbon consumption is difficult because: (a) variations can result not only from burned area, but from differences in fuel loads, fuel consumption, and the emission factors used to generate the atmospheric inputs from biomass burning; and (b) the papers reporting the estimates of emissions/carbon consumption rarely provide enough information to analyze the different factors that contribute to the estimates. To assess the effects of variations in burned area on carbon consumption during wildland fires, we used the total carbon emissions reported as part of the GFED3 data set [*van der Werf et al.*, 2010] for the years 2001–2006. These years were selected based on the time periods covered by all of the satellite data products used in this comparison (GFED3, GLOBCARBON, L3JRC, and MCD45A1). For comparison to other data sets, the GFED3 database was aggregated from a cell size of 0.5 by 0.5 degrees to 1.0 by 1.0 degrees. Average carbon consumption from the GFED3 per cell for each year was calculated by dividing total carbon emissions per cell by total burned area per cell. For each year, a total burned area per 1.0 by 1.0 degree grid cell was calculated for the GLOBCARBON, L3JRC, MCD45A1 data sets. The burned area per grid cell was then multiplied by the GFED3 average carbon consumption to estimate carbon emissions, which were then compared for the eight different geographic regions.

2.3. Geographic Analyses

[47] To study longer-term patterns of burning over the past five decades for Canada and the U.S. (including Alaska) using fire management data, we divided Canada into two sub-regions and the conterminous U.S. into four sub-regions. Eastern Canada included all the provinces to the east of Manitoba, while western Canada included all areas to the west of Ontario. We used the geographic coordination regions of the National Interagency Coordination Center (NICC: http://www.nifc.gov/nicc/index.htm) to define the four sub-regions for the conterminous U.S. The northeastern sub-region used for this study included all states within the NICC Eastern region. The southeastern sub-region included all states within the NICC Southern region. The southwestern sub-region included all states within the NICC Southwestern, Southern California, and Northern California regions. For long-term analyses, we assumed that one-half the area burned in Texas occurred in each of the southeastern and southwestern sub-regions. Finally, the northwest sub-region included all

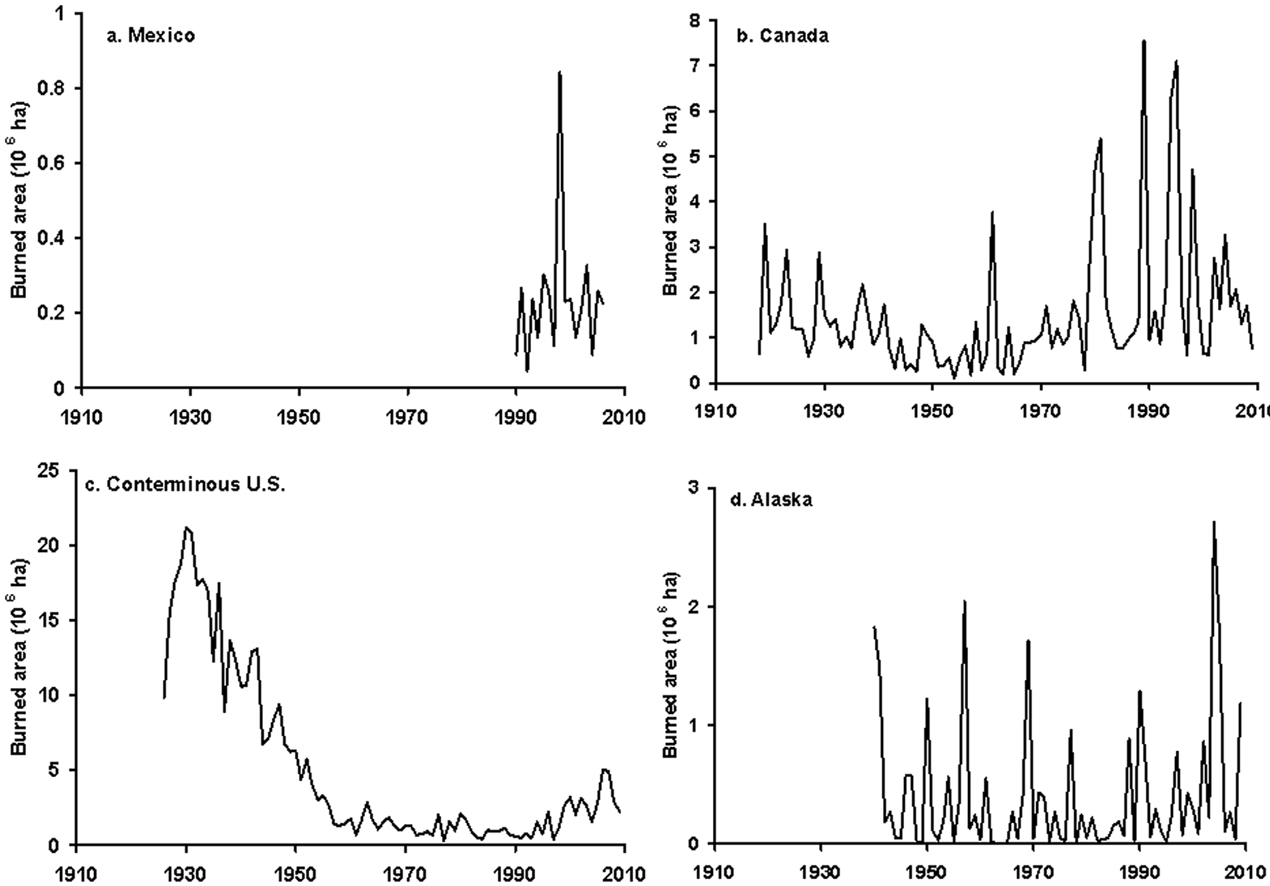

Figure 1. (a–d) Long-term patterns of annual burned area for the different regions of North America based on data provided from fire management records.

the states within the NICC Eastern and Western Great Basins, Rocky Mountain, Northern Rockies and Northwest Regions. Alaska was considered as a separate sub-region.

[48] For comparisons of satellite estimates of burned areas to those from fire management records, Canada was divided into two sub-regions (east and west) using 95° W longitude as a dividing line. The conterminous U.S. was divided into four sub-regions (northeast, southeast, southwest, and northwest) using 35° N latitude and 95° W longitude as dividing lines. Alaska and Mexico were considered to be separate sub-regions. These sub-regions were also used in comparing estimates of emissions from biomass burning (Section 2.2).

3. Results and Discussion

3.1. Burned Area Estimates

3.1.1. Land Management Data

[49] Burned area estimates are available from fire management records for Canada back to 1918, for Mexico back to 1990, for the Conterminous U.S. back to 1926, and for Alaska back to 1940 (Figure 1). Over the past two decades (the 1990s and 2000s), an average of 5.091×10^6 ha yr^{-1} of burned area has occurred across the North American continent (Figure 2). The lowest burned area occurred in 1992 (1.752×10^6 ha) and the highest in 1995 (8.144×10^6 ha). Average annual burned area increased by 24% between the 1990s (4.508×10^6 ha) and the 2000s (5.605×10^6 ha).

[50] Of all the regions of North America, Mexico experienced the lowest reported level of burning since 1990 (Figures 1a and 2): 0.235×10^6 ha yr^{-1} (compared to 2.200×10^6 ha yr^{-1} in Canada, 2.079×10^6 ha yr^{-1} in the Conterminous U.S., and 0.577×10^6 ha yr^{-1} in Alaska). Over the past two decades, fire records indicate that burned area has remained fairly constant in Mexico with exception of the large year in 1998. Because burned areas records for Mexico only exist back to 1990, evaluating longer-term trends is not possible.

[51] As discussed by *Gillett et al.* [2004], there was an apparent increase in fire activity in Canada from the 1960s through the 1990s compared to burned area during the previous decades (Figure 1b). The exact magnitude of this increase relative to fire activity in the first half of the 20th century is difficult to determine, however, because of the lack of fire records from certain regions of Canada prior to the 1950s. The available fire management data show increases in burned area from the 1960s through the 1990s. Since the 1950s, Canada has experienced the highest wildland fire burned areas across North American (1.808×10^6 ha yr^{-1}) compared to Alaska, the conterminous U.S. and Mexico. There is a high inter-annual variability in burned area in Canada, with large fire years (3 to 8×10^6 ha) the result of

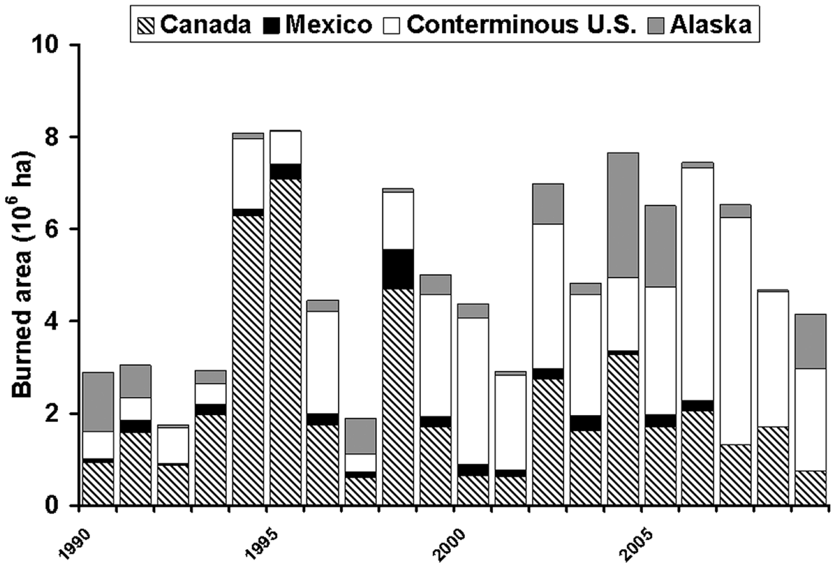

Figure 2. Comparison of annual burned area for Canada, Mexico, the Conterminous U.S. and Alaska for 1990 to 2009 based on data provided from fire management records. Data are unavailable for Mexico for 2007 to 2009.

drought conditions at regional scales (Figure 1b). Increases in burned area in Canada from the 1960s through the 1990s have been the result of the increase in the frequency of large fire years at regional scales [*Kasischke and Turetsky*, 2006].

[52] The long-term records show a very high level of wildland fire in the Conterminous U.S. in the 1920s through the 1940s (Figure 1c). However, 82% of the burning in the first half of the 20th century in the Conterminous U.S. occurred in the southeast and south-central states, where seasonal surface fires in scrub forests were quite common. In addition, the development of the forestry industry in the early 20th century also resulted in increased human caused fires in areas where forests were harvested. According to the annual burned areas reported for this period, a significant fraction of entire states burned in a single fire season. Fire records indicate that between the years 1926 and 1940, the area burned in Florida was equivalent to 4.5 times the entire area of the state, in Mississippi, equivalent to 3.4 times the entire area of the state, and in Georgia, equivalent to 1.7 times the entire area of the state (Figure 3). According to historical fire records, between 1927 and 1936, >30% of the entire state of Florida burned each year. The high burned area reported for the southern states raises questions on how burned area estimates were derived during this time period. In particular, were these estimates based on actual maps of fire perimeters? Or, did they represent "best guesses" based on the relative level of fire activity that occurred during a given year?

[53] Outside of the southern U.S. and the south-central U.S. (Texas, Kansas, and Oklahoma), the historical records showed that burned area changed very little between the first and second halves of the 20th century in all other regions of the Conterminous U.S.

[54] Beginning in 1998, U.S. fire management records included burned area from prescribed fires. These additional data show that since 1998, prescribed burning accounts for over 30% of all burned area in the conterminous U.S. (Table 1).

[55] In Alaska, the data indicate a decreasing trend in burned area between the 1940s and 1980s, and then a sharp increase in the 1990s and 2000s (Figure 1d). Like Canada, the increases were the result of increases in the frequency of large fire events [*Kasischke et al.*, 2010]. A number of additional trends have been observed based on the fire records from Alaska by *Kasischke et al.* [2010], and therefore will not be reviewed here. The data do show, however, that since 1998, prescribed fires have accounted for < 1% of the burned area in Alaska (Table 1).

[56] For Canada, the Conterminous U.S., and Alaska, there was a 61% increase in burned area over the past 50 years, from 2.808×10^6 ha yr^{-1} during the 1960s to 4.512×10^6 ha yr^{-1} during the 2000s. The patterns of decadal burning were different among the different sub-regions of Canada and the U.S. (Figure 4). Both the northeastern and southeastern

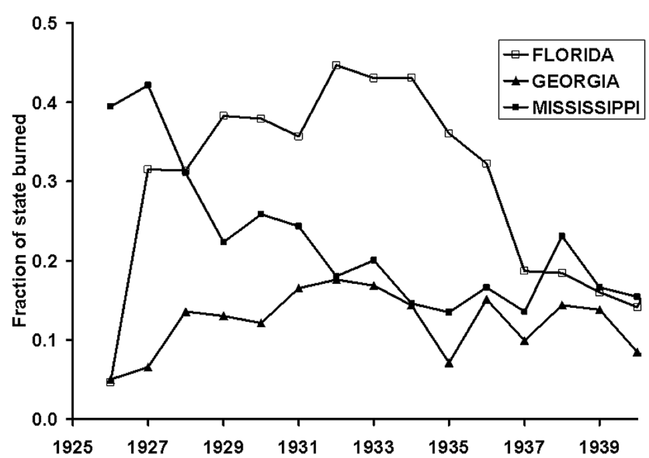

Figure 3. The fraction of the entire land area of Florida, Georgia and Mississippi that was reported as burned area for the years 1926 to 1940.

Table 1. Average Annual Area Burned (10^6 ha yr^{-1}) From Land Management Records and Satellite Data Sets for Different Regions of North America

	Fire Management Data										
	Annual Reports			Databases[a]			Remote Sensing Data				
Period	Total	Wildfire	Prescribed	USLFDB	AKLFDB	NFDB	GFED3	MCD45A1	L3JRC	GLOBC
					Mexico					
97–06	0.27						0.97			
01–06	0.21							1.15	5.94	
99–06	0.21									1.33
					Canada					
97–08	1.90					1.89	1.72			
01–08	1.88							1.07		
01–06	2.01								15.42	
99–07	1.75									9.75
					Conterminous United States					
97–08	2.72	1.93	0.86	2.03			1.44			
01–08	3.14	2.15	0.99					1.77		
01–06	2.87	1.89	0.98						18.86	
99–07	3.11	2.18	0.93							13.84
					Alaska					
97–08	0.65	0.65	0.01	1.03	0.64		0.40			
01–08	0.78	0.78	0.00					0.22		
01–06	0.99	0.99	0.00						1.94	
99–07	0.77	0.77	0.01							1.07

[a]USLFDB: U.S. Large Fire Data Base; AKLFDB: Alaska Large Fire Data Base; NFDB: National Fire Data Base (Canada).

U.S. experienced decreases in burned areas between the 1960s and 2000s. Overall average annual burned area decreased for the two eastern sub-regions by 57% between the 1960s and 2000s. For this period, burned area increased by a factor of five in the southwest U.S. and a factor of four in the northwest U.S., with the largest increase occurring in the northwest U.S. The increases in these regions followed a step-like pattern. Large increases in the southwest U.S. occurred between the 1960s and 1970s and 1990s and 2000s, where increases in the northwest U.S. occurred between the 1970s and 1980s and the 1990s and 2000s (Figure 4). In Canada, the largest increases in burned area occurred in the west, where there were patterns of large increases from the 1960s through the 1990s, and a sharp decrease in the 2000s. In eastern Canada, increases occurred in the 1960s through the 1980s, followed by a decrease in the 1990s.

[57] For Canada and Alaska, the burned areas within their large fire databases represent a significant fraction of the seasonal burned areas reported by fire management agencies: 99% for Canada and 98% for Alaska (Table 1). The fire events within the U.S. large fire database, however, represent only 75% of the total burned area reported from fire management agencies. We found that the LFDB created for the entire U.S. contained duplicate records for Alaska, with the same fire event being reported by multiple agencies in several years. This is not surprising since many large fires in Alaska occur in lands managed by several agencies. Because of this double-reporting, the U.S. LFDB over-reports burned area for many years in Alaska (Table 1). Because of the way different agencies report fires, it is difficult to separate the burned areas within the U.S. LFDB that have been double reported. For this reason, this data set should not be used when analyzing fires in Alaska until the data set has been corrected.

3.1.2. Satellite Estimates of Burned Area

[58] For Canada, the Conterminous U.S., and Alaska, the burned areas within the satellite-based GFED3 and MCD45A1 data sets are lower than the burned area reported by land management agencies, while in Mexico, they are higher (Table 1). The other two burned area products derived from satellite remote sensing data (L3JRC and GLOBCARBON) contain values that are significantly greater than those reported by fire management records for all regions (Table 1). For the years 2001–2006 (the years when data were available for all information products in all regions), across North America the GFED3 burned area estimates were 77%, MCD45A1 estimates were 74%, L3JRC estimates were 438%, and GLOBCARBON estimates were 701% of those reported by fire management agencies.

[59] An analysis of the sub-regional burned area data sets showed that even though the GFED3 burned area estimates were lower than those from the MCD45A1 data set, they had the highest correlation with fire management estimates of burned area for most regions (Figure 5). In 6 out of the 8 regions, the correlation between GFED3 and fire management burned area was greater that 0.90 for the six years used in the analysis. The only sub-region where the GFED3 burned areas did not have a strong correlation with land management estimates of burned area was the southeast U.S.; however, the correlation was low for all the remote sensing data sets for this sub-region (Figure 5). High correlations ($r > 0.90$) were also found for the MCD45A1 burned area data set for the boreal forest sub-regions, and significant correlations ($r > 0.70$) for the northeast and northwest U.S. sub-regions. The analyses showed that not only did the L3JRC and GLOBCARBON over-estimate burned area for each sub-region, but that there was also low correlation with burned area reported by land management agencies (Figure 5).

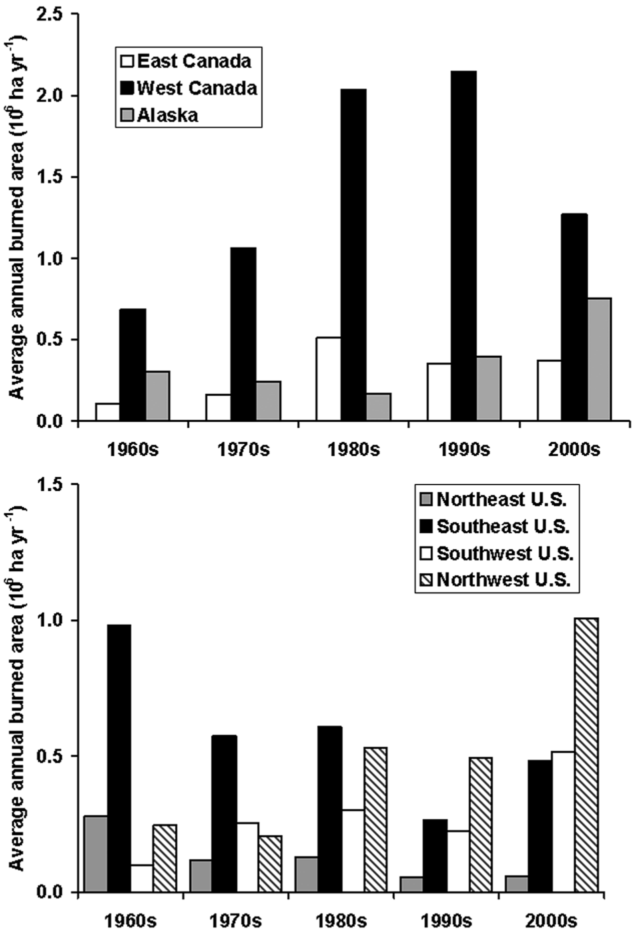

Figure 4. Decadal patterns of burned area for the different sub-regions of the U.S. and Canada for the past five decades (does not include area from prescribed burns).

3.2. Modeling of Burned Area

[60] Comparison of the data presented by *Spracklen et al.* [2009] and *Balshi et al.* [2009] and the model of *Duffy et al.* [2005] used by *Kasischke et al.* [2010] showed that each approach underestimated burned area for the boreal forest and western U.S. regions of North America (Figure 6). The best agreement was found for *Balshi et al.* [2009], where predicted burned area was 62% of the burned area provided by fire management records. The poorest agreement was found for *Spracklen et al.* [2009], where predicted burned area was only 42% of the burned area provided by fire management records.

3.3. Reliability of Long-Term Fire Information Products

3.3.1. Burned Area Estimates

[61] When using long-term data sets to analyze the impacts of fire on carbon cycling, it is desirable to develop uncertainty values for the burned area estimates and other parameters used in models to estimate carbon flux and storage [see, e.g., *French et al.*, 2004]. In this section, we discuss factors that control uncertainties in burned area estimates that are available for modeling the impacts of fire on carbon cycling in North American forests.

[62] Over the past 130 years since scientists and managers began compiling data to estimate burned area in North America, the methods used for mapping fires have continuously evolved in response to advances in technology. To understand the influence of technology, consider the three factors required to estimate burned area for large fire events (which provides a foundation for estimating burned area over large regions). First, access to the areas where fires occur is needed. Second, there must be a means to observe the entire fire perimeter. And third, there must be a way to accurately locate and map the position of the fire perimeter. Below, we will discuss how advances in technology have provided the means to address the above information requirements within the United States. Similar arguments could be made for Canada and Mexico based upon the particular set of circumstances for these countries.

[63] The first technological development that addressed these information needs was the creation of a surface transportation network across the U.S. This included the development of railroads in the late 1800s and early 1900s, the continuous expansion of road networks into remote areas throughout the 20th century, and the rapid expansion of the automotive industry that provided the basis for using the expanded road network to conduct fire reconnaissance. These developments all provided an ever-expanding ability to access a larger portion of remote areas where wildland fires were common, especially in the western U.S.

[64] In spite of these developments, there was still a considerable area in the U.S. that could not be accessed by roads, especially in Alaska. These limitations were initially overcome by the development of the aviation industry, in particular over the last half of the 20th century. While aircraft were available for observing fires in remote regions as early as the 1920s, aviation resources were not incorporated into fire management agencies until the late 1940s, when surplus aircraft and a trained pilot force became available at the end of World War II. The ability to map fires from satellite imagery beginning in the mid-1970s overcame the need for any sort of ground or airborne transportation to access areas where fires occurred.

[65] Once access is gained to areas where fires occur, there must be some means to observe the perimeters for individual fire events. For large fire events, precise mapping of fire perimeters is not feasible using ground transportation alone, and requires some sort of elevated observation point (e.g., a mountain top, fire tower, or aerial platform). The means to adequately address this requirement was not available in the U.S. until the late 1940s, when fire management agencies began to implement capabilities for the aerial monitoring of fires in a systematic fashion. Again, the availability of satellite remote sensing imagery beginning in the 1970s provided a solution to address this issue as well.

[66] Finally, once the means became available to gain access to and observe the perimeter of the fire event, the ability to accurately locate the perimeter of the fire event was needed. While USGS produced its first map of the United States in 1879, maps at a scale needed for locating large fire events were not available across the entire U.S. until the 1970s. Prior to the production of these maps, fire managers were not only required to produce maps of fire perimeters, but also the baseline maps of the areas where the fires occurred, including information on location (latitude

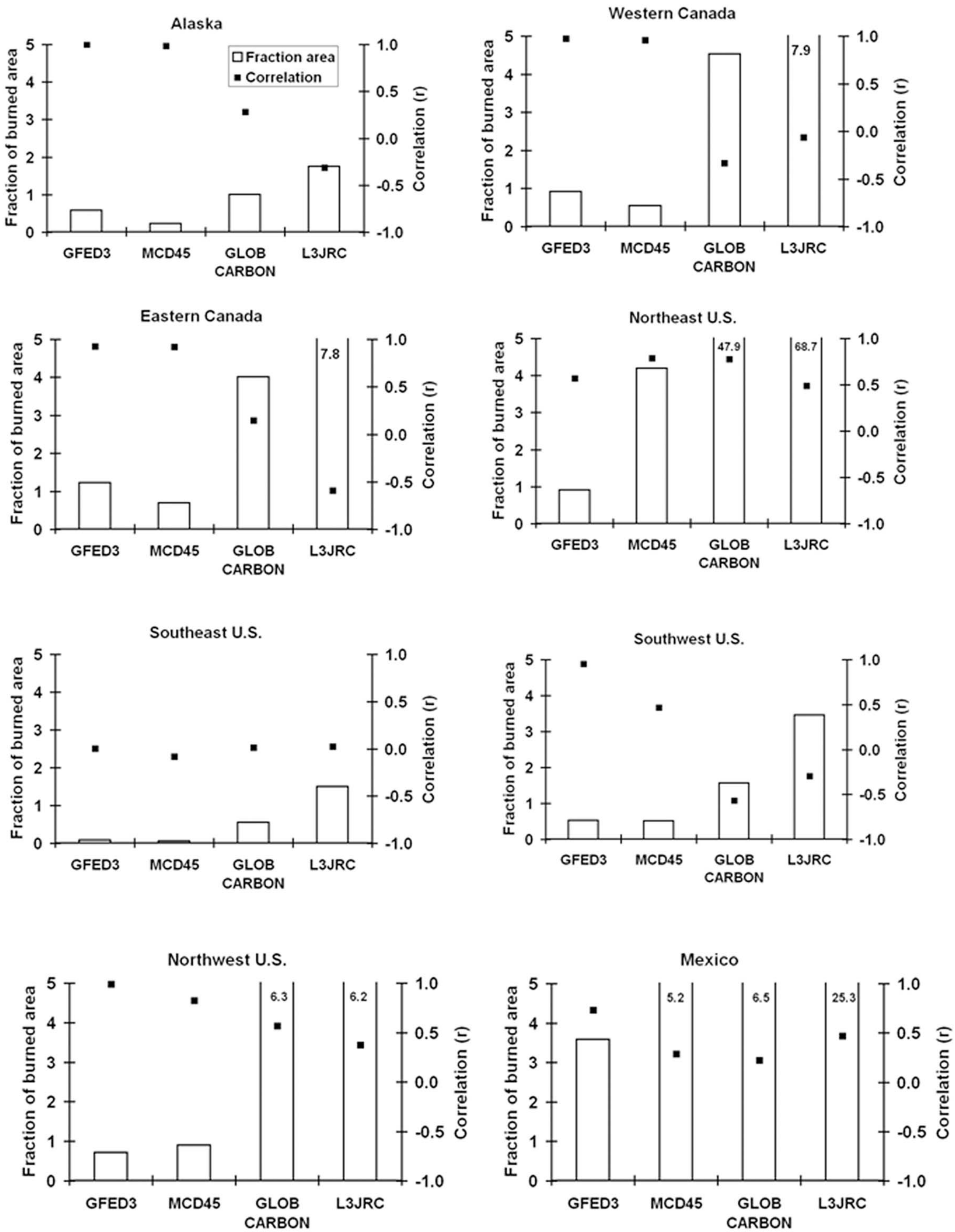

Figure 5. Comparison of burned area from satellite data sources for 2001 to 2006 to burned area from fire management records for the eight sub-regions of North America. The left-hand y axis presents the satellite burned area divided by the land management burned area, and the right-hand y axis shows the linear correlation (r) between the two different burned area values. Ratios of satellite burned area to land management burned area greater than 5 are presented as numbers on the plots.

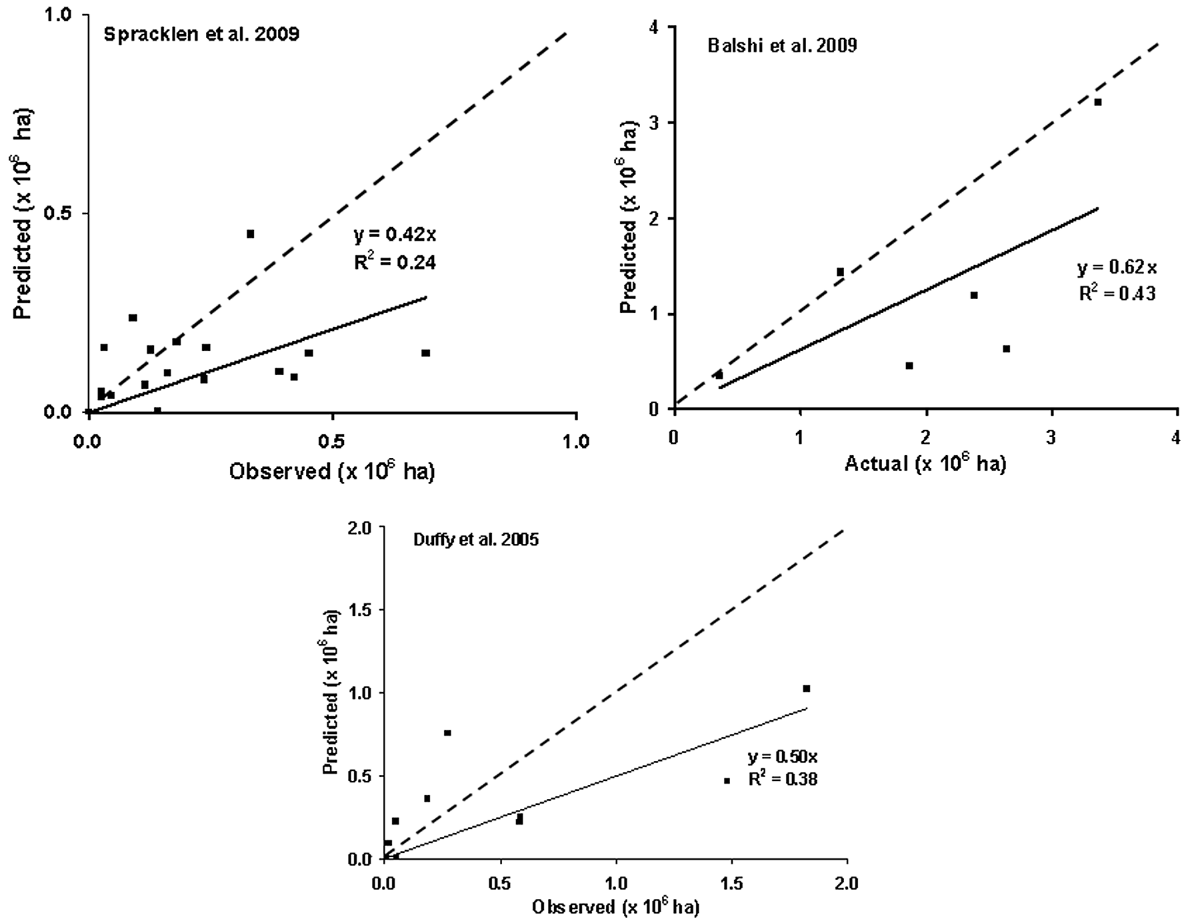

Figure 6. Plots of model burned area as a function of land management burned area from three models. The dashed line represents the 1:1 line between modeled and land management burned area, where the solid line represents the actual relationship.

and longitudes of the region) and the locations of the prominent cartographic features of the region (e.g., roads, streams, rivers, lakes, etc.) [see, e.g., *Kasischke et al.*, 2002, Figure 2]. Thus, the accuracy of the fire perimeter maps in terms of estimating burned area depended upon the cartographic skills of the observer, even when baseline maps became widely available. This mapping limitation was to some extent overcome by the availability of satellite remote sensing imagery beginning in the mid-1970s, if the fire management agency had the resources to obtain and process the satellite data. The development of global positioning systems (GPS) in the early 1990s provided a convenient means for locating the perimeters of fire events. Using the data from GPS within a GIS, maps of fire perimeters can easily be generated, as can highly accurate estimates of burned area.

[67] As discussed earlier, the use of satellite imagery in many cases provides the optimal solution for addressing all the requirements for mapping burn perimeters and estimating burned areas. Even though remote sensing data suitable for mapping burned area over large areas has been available since the mid 1970s, it has been only recently that programs have been developed to exploit this technology. In particular, in the U.S., the Monitoring Trends in Burn Severity (MTBS) project is in the process of generating a perimeter map for all fire events larger than 400 ha in size across the U.S. for the years 1984–2010. In many instances, fire managers now use satellite data as the primary means for mapping perimeters of fire events.

[68] Why hasn't satellite remote sensing imagery been adapted as the primary means for fire management agencies to map fire perimeters? The answer to this question is complex. First, the in-house capabilities within land management agencies to process and analyze geospatial data have slowly evolved over the past two decades. It has only been during the late 2000s that the infrastructure (both technology and human resources) needed to routinely process and analyze satellite been implemented across all agencies responsible for fire management. Second, there are issues related to the production of timely and/or redundant information. Geospatial technicians are now often called upon to produce continuous updates of fire perimeter maps based on using observations made with GPS collected from aerial platforms. It is not uncommon to produce updates on a daily basis, especially for large, active fire events. This information requirement cannot be fulfilled using medium resolution satellite data because of the repeat frequency of these satellites. Because of this practice, the regeneration of a fire perimeter map using satellite data collected at the end of a fire season is often viewed as producing redundant

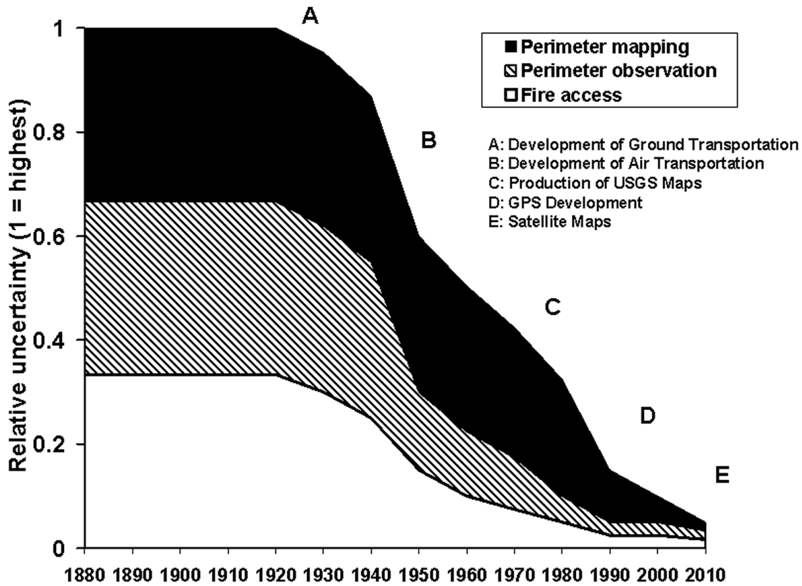

Figure 7. Patterns of relative uncertainty in estimating burned area over time in the United States based on advances in mapping technologies.

information. Thus, the use of satellite data for mapping fire perimeters over large areas only occurs when fire management agencies do not have the resources to monitor fires in remote regions [see, e.g., *Epp and Lanoville*, 1996].

[69] The evolution of technology over the past century has played a central role in improving the accuracy of estimates of burned area in the United States and Canada, yet few studies have assigned error bounds to historical burned area estimates [see, e.g., *Kasischke et al.*, 2002]. For example, what is the error or uncertainty bound on the estimate of 22 million ha burned in the early 1930s for the U.S. that is reported in the annual reports of Wildland Fire Statistics (USDA) given the restrictions placed on mapping fires based on the available technology of that era?

[70] To examine this uncertainty issue, a simple thought exercise was carried out on how the development of various technologies has influenced relative uncertainties in estimating burned area. Uncertainty was rated on a relative scale of 0 to 1/3 for three different categories: fire access, perimeter observation, and perimeter mapping. The effects of five different technological advances were evaluated in terms of the reliability of burn estimates in the 3 categories: development of a ground transportation network; development of air transportation; production of USGS maps; GPS development; and production of satellite maps.

[71] The results from this assessment are presented in Figure 7, which indicates there was likely very high uncertainty in burned area estimates prior to 1950, and that the development of technologies has gradually reduced uncertainties over time. Note that this assessment is very rudimentary in that it is based upon an incomplete understanding of the practices used for mapping fires during years prior to 1950, and on best guesses as to how advances in technologies affected the uncertainties in the three areas. It very well could be that the weighting for the uncertainty categories might be different than those used to generate Figure 7. For example, perimeter observation and mapping may play a greater role in uncertainties than fire access. Regardless of the assumptions used, we believe the basic trend in Figure 7 to be consistent with reality, with very high levels of uncertainties existing prior to the 1920s, and a continuous decrease in uncertainties due to the implementation of different technologies over time.

3.3.2. Seasonal Fire Activity

[72] Care must also be taken in using other fire information reported by management agencies. While some have attempted to use fire management records to estimate changes in fire season-length [see, e.g., *Westerling et al.*, 2006], this approach may be problematic. In particular, there are often two criteria used to designate a fire as being out. The first designation for an end date is based on the physical characteristics of a fire, e.g., when does the fire perimeter stop growing, or when does smoldering combustion of fuels that might provide the basis for further fire spread end. The second designation for an end date is based on administrative considerations. The logistics for fire management activities are often accounted for on an individual fire basis. In the U.S., this approach was developed for several reasons. First, areas that are burning in large fire events often fall under the jurisdiction of different land management agencies that have individual budgets and manpower for fire management. Establishing a single financial accounting system for each fire event provides the basis for sharing of resources between agencies in managing large fire events, as well as the flexibility to shift resources between fire events as circumstances dictate. Second, this approach allows for sharing of resources between fire management agencies, especially the shifting of resources from areas with low fire activity to areas with high fire activity. During large fire years especially, individual fire events are often not declared out until late in the fire season because of limited resources for actually determining whether a fire event has physically ended and the need for flexibility to administratively assign resources to an event

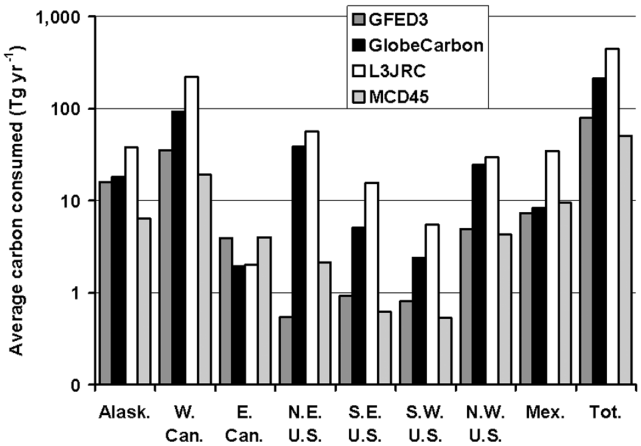

Figure 8. Average annual carbon consumed for the different sub-regions of North America based on differences in burned area between the different satellite data products.

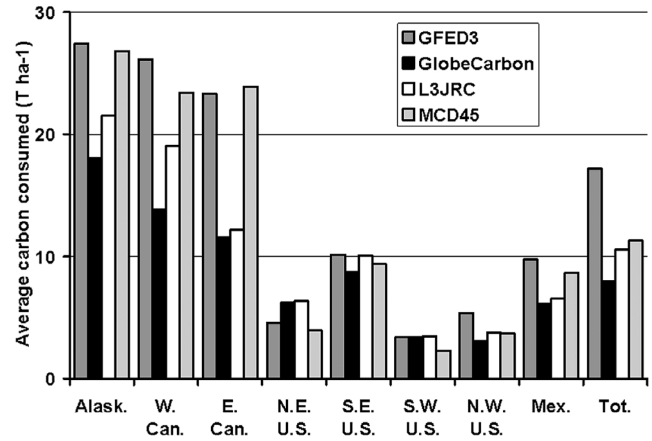

Figure 10. Average carbon consumed from biomass burning in the different sub-regions of North America using the different satellite burned area products.

should it become active again. As an example, during the large fire season of 2004 in Alaska, daily fire reports for individual events as well as daily observations of fire hot spots from thermal IR satellite remote sensing systems showed that fire activity on the majority of large fire events ended in early September. Yet for management purposes, the out dates for a large number of fire events were in mid to late October. In some cases, fires declared out often continue to smolder and become the source of fire ignitions during the following fire seasons. This was the case in Alaska for several fires that started in May of 2010.

3.4. Impacts of Burned Area on Estimates of Carbon Consumption

[73] The estimated amounts of average carbon consumed for the different fire information products was 79.7 Tg yr^{-1} for the GFED3 burned area product, 211.5 Tg yr^{-1} for the GLOBCARBON product, 445.6 Tg yr^{-1} for the L3JRC product, and 50.7 Tg yr^{-1} for the MCD45A1 product. These results are consistent with the observations that burned area estimates from GLOBCARBON and L3JRC were considerably greater than those from GFED3, and were slightly lower in the MCD45A1 product. There was considerable variability in the relative differences in average annual carbon consumed between the products in the different sub-regions (Figure 8), which correspond to some degree to differences in burned area across the sub-regions (Figure 9). In addition, the differences in total carbon consumed are also due to the fact that the areas mapped as being burned by the GLOBCARBON, L3JRC, and MCD45A1 products had lower fuel levels than those mapped by the GFED3 products, which resulted in lower fuel consumptions. The average fuel consumption using the GFED3 product 17.2 t C ha^{-1}, compared to 8.0 t C ha^{-1} for the GLOBCARBON product, 10.6 t C ha^{-1} for the L3JRC product, and 11.3 t C ha^{-1} for the MCD45A1 product. Again, there were considerable differences in the differences in average fuel consumption across the different sub-regions (Figure 10).

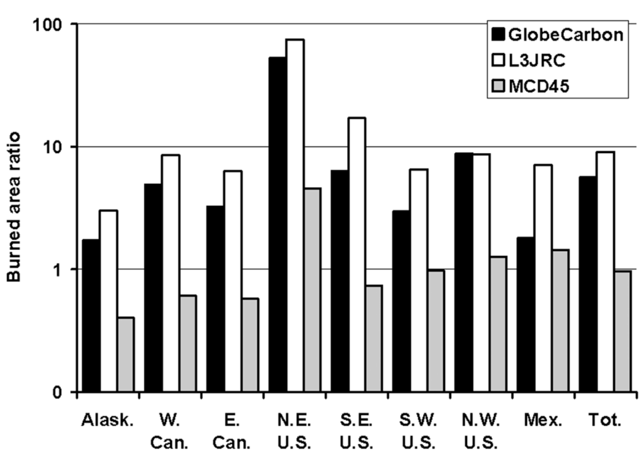

Figure 9. The ratio between GFED3 burned area and burned area from the GLOBCARBON, L3JRC and MCD45A1 products (other product burned area/GFED3 burned area) for the different sub-regions of North American.

4. Conclusions and Recommendations

[74] Many different data sets exist for estimating burned area and fire frequency in the forests of North America. The most extensive of these data are from fire management records, which include perimeters of large fire events for most of North America back to 1980, with longer records being available for Canada (back to 1959) and Alaska (1950). The fire perimeter data are more limited for the conterminous U.S., and are incomplete because they do not contain fire events from non-federal sources. The burned area data are most limited for Mexico. While fire records exist for Canada and the Conterminous U.S. back to the early 20th century, use of these data for assessing the impacts on carbon cycling should take into account the limitations of these data sets. Some regions in Canada were not monitored for fire, and the large burned areas reported in the southern U.S. during the early 20th century are likely due to educated guesswork, not on the actual mapping of the actual extent of fire. Caution needs to be used in using historical fire records in carbon cycle studies because of poor documentation of

how data were collected and archived during the first half of the 20th century. It is very likely that the available data for the conterminous U.S. significantly overestimate burned area, but until a thorough review of methods used to collect and compile these data is carried out, assigning uncertainties is not possible. As part of efforts to compile burned area data sets for carbon cycle sciences studies discussed below, research on the uncertainties associated with each data set needs to be conducted.

[75] Information in fire management records are not suitable for assessing changes in seasonality of burning because many records do not include the actual time of the end of a fire event. Satellite thermal IR (e.g., hot spot) data are the most dependable source of data for assessing fire timing and duration.

[76] Continental-scale data on burned area and seasonality of burns from satellite remotely sensed data are available back to 1997. The GFED3 and MCD45A1 estimates of burned area are lower than those reported by fire management agencies, while the L3JRC and GLOBCARBON data sets provide burned area estimates that are significantly greater than those reported by fire management agencies. Because of their availability over longer time periods, burned area information from land management agencies is more useful in carbon cycle studies. In studies that require temporal information on fire occurrence (such as estimating emissions from biomass burning), satellite burned area products may be more appropriate, with the GFED3 being the most reliable.

[77] Fire management agencies are increasingly making use of moderate resolution remote sensing data (e.g., Landsat TM/ETM+) for mapping fires and estimating fire severity. These products offer the opportunity to not only produce accurate fire perimeter maps, but also the ability to map unburned islands within perimeters and have the potential to provide information on fire severity. While the MTBS program is producing burn severity maps for the entire U.S. for the period of 1984–2010 based on correlations between dNBR and CBI, these products have limited utility at this point for carbon cycle science. CBI is a very generalized measure of fire severity, and efforts are needed to assess the utility of the satellite data products for estimating specific surface characteristics that are used to assess the impacts of fire on terrestrial carbon cycling, including fraction of biomass consumed during the fires, rates of tree mortality, and other characteristics that can be used to assess the impacts of fire on post-disturbance recovery.

[78] The use of Fire Radiative Power (FRP) and Fire Radiate Energy (FRE) products available from MODIS has the potential to be used for assessing fire severity as well as estimating emissions from fires. The use of these products in carbon cycle science, however, is dependent on validating the information produced from these products as well as developing approaches to extrapolating information collected from a limited number of points within a specific fire event over the entire extent of the event.

[79] While many data sources exist to quantify fire activity, efforts are still needed to improve the utility and access of these data for carbon cycle science studies. Historical annual burned area records for different states, provinces, and territories in Canada and the U.S. need to be compiled and made available within a single-database. Fire management records and archives of data for individual, large (>200 ha) fire events in the Conterminous U.S. need to reviewed in order to create a single record of these events. While the MTBS program will have created fire perimeter and dNBR maps for many of the large fires in the U.S., it does include all fire events because of Landsat data availability issues, as well as the fact that the approach used to select the fires included in this data set may have overlooked a number of large events. Future efforts should focus on: (1) identifying missing fire events in the U.S. and adding them to the MTBS archive if data are available; and (2) carrying out a similar activity for Canada and Mexico for the period of 1984–2010. Such a data set would provide information of the actual patterns of burning as a function of vegetation type and topography. Furthermore, data from Landsat MSS data over fire events between 1974 and 1984 could be analyzed as well, creating an even more extensive burned area data set for carbon cycle science. Finally, while the use of satellite remote sensing data to estimate fuel consumption and fire severity hold great promise, research needs to be conducted to develop and validate specific products for use in analyzing the impacts of fire on the carbon cycle.

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