Assessing satellite-based fire data for use in the National Emissions Inventory

Amber J. Soja[a], Jassim Al-Saadi[b], Louis Giglio[c], Dave Randall[d], Chieko Kittaka[e], George Pouliot[f], Joseph J. Kordzi[g], Sean Raffuse[h], Thompson G. Pace[i], Thomas E. Pierce[f], Tom Moore[j], Biswadev Roy[g], R. Bradley Pierce[k] and James J. Szykman[l]

[a]National Institute of Aerospace (NIA), NASA Langley Research Center, 21 Langley Boulevard, MS 420, Hampton, VA 23681-2199, USA
Amber.J.Soja@nasa.gov or asoja@nianet.org
[b]NASA Langley Research Center, 21 Langley Blvd, MS 401B, Hampton, VA 23681-2199
j.a.al-saadi@nasa.gov
[c]Science Systems and Applications, Inc., 10210 Greenbelt Rd., Suite 600, Lanham, MD 20706, USA
louis_giglio@ssaihq.com
[d]Air Sciences Inc., 1301 Washington Ave, Ste 200, Golden, CO 80401, USA
drandall@airsci.com
[e]Science Systems and Applications, Inc., NASA Langley Research Center, 21 Langley Blvd, MS 401B, Hampton, VA 23681-2199, USA
Chieko.Kittaka-1@nasa.gov
[f]EPA Office of Research and Development (ORD), 109 T.W. Alexander Drive, Room E-231I, Research Triangle Park (RTP), NC 27711, USA
Pouliot.George@epamail.epa.gov, pierce.tom@epa.gov
[g]USEPA Region 6, 1445 Ross Ave., Dallas, TX 75202, USA
Kordzi.Joe@epamail.epa.gov; Roy.Dev@epamail.epa.gov
[h]Sonoma Technology, Inc. (STI), 1455 N. McDowell Blvd., Petaluma, CA 94954, USA
sraffuse@sonomatech.com
[i]EPA Office of Air Quality Planning and Standards (OAQPS) (retired), Environmental Sciences Division, 109 T.W. Alexander Dr. M/S: E243-05, RTP, NC 27711, USA
Pace.Tom@epamail.epa.gov, TLP@bellsouth.net
[j]Colorado State University, WRAP Tech. Coordinator, 106 CIRA Bldg., Fort Collins, CO
MooreT@cira.colostate.edu
[k]NOAA National Environmental Satellite, Data, and Information Service, 1225 W Dayton Street, room 203, Madison WI, 53706-1612, USA
brad.pierce@noaa.gov
[l]Environmental Protection Agency, NASA Langley Research Center, 21 Langley Boulevard, MS 401B, Hampton, VA 23681-2199, USA
james.j.szykman@nasa.gov

Abstract. Biomass burning is significant to emission estimates because: (1) it can be a major contributor of particulate matter and other pollutants; (2) it is one of the most poorly documented of all sources; (3) it can adversely affect human health; and (4) it has been identified as a significant contributor to climate change through feedbacks with the radiation budget. Additionally, biomass burning can be a significant contributor to a regions inability to achieve the National Ambient Air Quality Standards for PM 2.5 and ozone, particularly on the top 20% worst air quality days. The United States does not have a standard methodology to track fire occurrence or area burned, which are essential components to estimating fire emissions. Satellite imagery is available almost instantaneously and has great potential to enhance emission estimates and their timeliness. This investigation compares satellite-derived fire data to ground-based data to assign statistical error and helps provide confidence in these data. The largest fires are identified by all satellites and their spatial domain is accurately sensed. MODIS provides enhanced spatial and temporal information, and GOES ABBA data are able to capture more small agricultural fires. A methodology is presented that combines these satellite data in Near-Real-Time to produce a product that captures 81 to 92% of the total area burned by wildfire, prescribed, agricultural and rangeland burning. Each satellite possesses distinct temporal and spatial capabilities that permit the detection of unique fires that could be omitted if using data from only one satellite.

Keywords: biomass burning, remote sensing, area burned, Environmental Protection Agency, climate change, Arizona and Oregon.

1 INTRODUCTION

In 1990, Congress amended the Clean Air Act (CAA), which strengthened the United States Environmental Protection Agency's (EPA) mandate to address regional haze. Regional haze refers to visibility impairment that is caused by the emission of air pollutants from numerous sources located over a wide geographic region that may encompass several states. The EPA Office of Air Quality Planning and Standards (OAQPS) published a rule in 1999 to address regional haze in 156 Class I areas, which include national parks and wilderness areas such as the Grand Canyon, Yosemite, the Great Smokies and Shenandoah [1]. The rule requires the states, in coordination with the EPA, the National Park Service, U.S. Fish and Wildlife Service, the U.S. Forest Service (USFS), and other interested parties, to develop and implement State Implementation Plans (SIPs) to reduce the pollution that causes visibility impairment [http://www.epa.gov/air/visibility/program.html].

As a result of the Regional Haze rule, five Regional Planning Organizations (RPO) were formed across the U.S. in an effort to coordinate affected states and tribes and to initiate and coordinate activities associated with the management of regional haze and other air quality issues. The five RPOs are: the Central Regional Air Planning Association (CENRAP), the Midwest Regional Planning Organization (Midwest RPO), the Mid-Atlantic and Northeast Visibility Union (MANE-VU), the Visibility Improvement State and Tribal Association of the Southeast (VISTAS), and the Western Regional Air Partnership (WRAP). The RPOs are tasked with, among other things, assisting the States in the development of regional haze SIPs. These SIPs (due December 17, 2007) included long term strategies to control regional emission sources, with the goal of returning to natural visibility conditions at 156 Class I areas by 2064.

Haze-causing pollutants (mainly $PM_{2.5}$ - particles 2.5 microns or less in diameter) are directly emitted to the atmosphere and formed secondarily through the combination of smaller precursor particles. Activities that can lead to the formation of $PM_{2.5}$ include electric power generation, various industrial and manufacturing processes, truck and auto emissions, construction activities and biomass burning. Biomass burning (wildfire, prescribed burning and agricultural burning) is a major source of $PM_{2.5}$, and if poorly quantified, can introduce significant error when modeling regional haze. In particular, biomass burning is often influential on the top 20% worst air quality days, which is a significant indicator when assessing the causes of regional haze [2, 3]. The inability to adequately define biomass emissions is due to the fact that the U.S. does not have a standard database of fire events or area burned for any year. Several organizations (i.e. USFS, Bureau of Land Management) have limited data for their particular geographic regions, but these data are not collected by a standard methodology, even within an organization. Additionally, these data exclude any biomass burning events that occur outside of these boundaries and fail to capture small fires

(<100 acres or 0.40 km^2), agricultural (e.g., sugar cane, wheat/rice stubble, and grasses), private or non-federal rangeland burning.

The EPA, in its mission to protect human health and the environment, is mandated to maintain good air quality for current and future generations. Under the CAA, the OAQPS is responsible for setting standards for pollutants that are considered harmful to people and the environment, and these are known as the National Ambient Air Quality Standards (NAAQS). A key tool in EPA's arsenal is the National Emissions Inventory (NEI), which is a national database of air emissions information for each area of the country, compiled by the EPA on an annual basis. It contains information on stationary and mobile sources that emit criteria air pollutants and their precursors, as well as hazardous air pollutants. The NEI is used for a number of critical environmental management and policy activities including regulation setting and regional strategy development for attainment of the NAAQS.

Previous EPA methodologies for estimating biomass burning emissions involve the use of fire activity data from a variety of sources and the application of ratio methods or growth factors when current year data are not available or incomplete. For instance, to estimate forest and wildfire emissions for the 1999 emissions year, the EPA used fire activity data for the years 1985-1998 obtained from the U.S. Department of Interior and the USFS for Non-Grand Canyon States. After the emissions estimates were produced, they were often distributed from an aggregated state level to a county level using data from a prior year(s). This often led to large errors and inaccuracies when comparing where emissions were shown to occur and where actual biomass burning occurred [4]. Recently, in a large part as a result of this work, the EPA had begun to include satellite data in the NEI [5].

Although this work focuses on providing the EPA with the necessary background and statistical information they need for adequately using remotely sensed data to enhance the NEI's biomass burning emissions, the technology described herein are transferable to any future effort to inventory the contribution of biomass burning to atmospheric carbon emission levels. According to the Intergovernmental Panel on Climate Change, Fourth Assessment Report, there is great uncertainty concerning the radiative forcing due to biomass burning [6]. Emission inventories show more significant differences for biomass burning aerosols than for aerosols of fossil fuel origin [7]. Thus, this research, by elucidating area burned for improving the emissions inventory for biomass burning, would add to the science of climate change and future comprehensive regulatory efforts to control anthropogenic carbon dioxide emissions in response to the problem of climate change.

Estimating fire emissions from the ground requires four major parameters (Fig. 1) [area burned, fuel (amount available in ecosystem), fuel consumption (amount consumed, directly relates to severity and weather) and emission factors (relates total carbon to particular species)]. This ground-based methodology has been applied and improved in many ecosystems for decades [8-16]. Area burned is one of the primary parameters necessary to estimate emissions, and it is considered to be the largest source of error in our nations NEI. Area burned error can result in emissions error that is equal to the discrepancy (i.e. half = half the emissions). Each of these parameters has error associated with its estimate, however the concentration of this investigation is on quantifying detailed and large-scale error in satellite-based products as compared to the "trusted" ground-based inventory data from 2002.

1.1 Objectives

The EPA, RPOs, federal, state and local organizations are responsible for and coordinate the generation of the NEI and are also users of the NEI to meet their regulatory and policy needs. Biomass burning emissions is only one element of the NEI, however it is one that has been traditionally poorly defined.

The EPA focuses on producing a detailed NEI every 3 years. For 2002, the EPA and RPOs advocated the development of a reliable "best available" ground–based fire dataset,

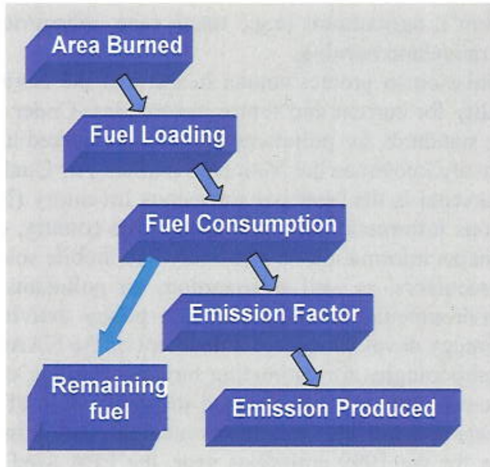


Fig. 1. Factors used to estimate pyrogenic carbon emissions [17].

upon which analyses and SIPs would be based. Hence a substantial amount of time and monetary resources were expended to produce the best available ground-based fire dataset in existence for the US. This project is specifically designed to compare satellite-based area burned data products to the "trusted" 2002 ground-based inventory to establish credibility in satellite data using the dataset in which the customers are most confident.

Because the EPA is responsible for the development of the NEI, the EPA requires knowledge of the spatial and temporal ability of satellite-based fire data and its associated potential error. Additionally, the EPA requires a methodology that will be consistent into the future, so this investigation focuses on satellite data that has been consistently available and predicted to be available in the future. Without an understanding of the capability of satellite data to describe the spatial, temporal and size domains of fire in the US, emission estimates using these data are uncertain.

For these reasons, the ability of satellite data to quantify fire is statistically analyzed for 2002 by (1) comparing ground and satellite data to identify spatially and temporally coincident fire events; (2) quantify the amount of area burned that can be identified by satellite; and (3) inter-compare satellite-based area burned products. Additionally, we will use lessons learned to define a methodology designed to capture the maximum number of fires, from small agricultural to larger wildfires, in Near-Real-Time (NRT) by incorporating data from all the satellites [14, 18-20]. One difference between this investigation and previous work is this study analyzes fire over a large spatial and temporal domain using ground-based data, as opposed to concentrating on a few large fires or using satellite data to validate satellite data.

2 METHODS

First, in a detailed analysis, satellite–derived fire data are compared temporally and spatially to ground-based fire datasets from Oregon (OR) and Arizona (AZ). Satellite data are used to quantify the number of fires and estimate area burned in Oregon (July 2002) and in Arizona (August and September 2002). In order to thoroughly test the data, we focused on two distinct ecoregions. Oregon is defined by a cool, dark vegetation-filled background that typically enhances a satellites ability to detect fire, and Arizona is a reflective (sand, minerals), hot environment that challenges satellite fire detection. In developing this research, it is assumed that either a comprehensive satellite-based area burned product is not available for the continental U.S. (CONUS), and/or emissions are time sensitive and must rely on active fire detections.

Then, several satellite-based fire products are compared to ground-based area burned data from the 13 western region states.

2.1 Satellite data

Two satellite-derived products are considered in this analysis, the first from Geostationary Operational Environmental Satellite (GOES) Automated Biomass Burning Algorithm (ABBA) data and the second from MODerate Resolution Imaging Spectroradiometer (MODIS) thermal anomaly data. The reason for comparing two distinct satellite instruments is to take advantage of the unique temporal resolution of GOES (30 minute data, 16 km^2 nadir resolution) and the unique spatial resolution of MODIS (twice daily, 1 km^2 nadir resolution). Data are taken from four satellites in this investigation (GOES east, GOES west, MODIS Terra, MODIS Aqua).

Both MODIS and GOES ABBA products have demonstrated their ability to detect biomass burning in numerous ecosystems [21-29]. The GOES ABBA algorithm uses GOES visible, middle infrared and thermal infrared bands to detect fires. After a fire pixel is located, the algorithm incorporates temperature and ancillary data (i.e. ecosystems, water vapor attenuation, solar reflectivity) to quantify the instantaneous size of a fire. The MODIS instrument exploits the middle infrared and thermal infrared bands to identify thermal anomalies and generate fire locations. Both of the algorithms take advantage of the sensitivity of these wavelengths to fire [30].

The historic filtered GOES ABBA data are downloaded from the Fire Locating and Modeling of Burning Emissions (FLAMBE) website (http://www.nrlmry.navy.mil/flambe/index.html). Data are available every half hour from both GOES east and GOES west for North America in 2002. Version 5.9 is exclusively available at the beginning of the study period and version 6.0 is exclusively available at the end of the study period. When both datasets are available, version 6.0 is utilized in this investigation. The text data are integrated into daily data files, and then the data are combined into one Geographic Information System (GIS) spatial file, which includes ancillary data (i.e. date, ecosystem, fire flag). In the raw GOES ABBA data product, fire data are flagged as processed (0), saturated (1), cloudy (2), high probability (3), medium probability (4) and low probability (5) fire data. Low probability data are excluded from this analysis. Only the GOES ABBA processed data (flag 0) contain an estimate of the fire size, calculated for that moment of detection (instantaneous fire size) (OR - range 0.005 – 3.26 km^2, mean 0.40 km^2; AZ - 0.005 – 1.77 km^2, mean 0.23 km^2). Flags 1 through 4 represent valid fire detections, however the information was not available to estimate a precise fire size (i.e. sensor saturated). Therefore, because we are interested in area, the instantaneous fire size is assumed to be consistent within ecoregions. Then, the mean instantaneous fire size is calculated using the processed data within an ecoregion (flag 0), and this mean fire size is assigned to fires in flag categories 1 through 4. Consequently, instantaneous fires sizes are calculated for flags 1 through 4 or provided in the GOES ABBA processed flag 0 data. As described above, a GOES instantaneous fire size represents the size of a fire burning at the moment of detection. Each distinct instantaneous fire size is defined by a polygon around the reported latitude and longitude point locations in GIS. For this analysis, GOES area burned during a fire event is defined as the sum of the instantaneous fire sizes that are spatially and temporally consistent with the fire event.

Next, GOES area burned is buffered to realistically assess the coincidence in these data and ground-based data. The GOES instantaneous fire sizes are surrounded by a 10 km radius buffer (~ 0.05 degrees) to account for: (1) the spatial resolution of the instrument; (2) the

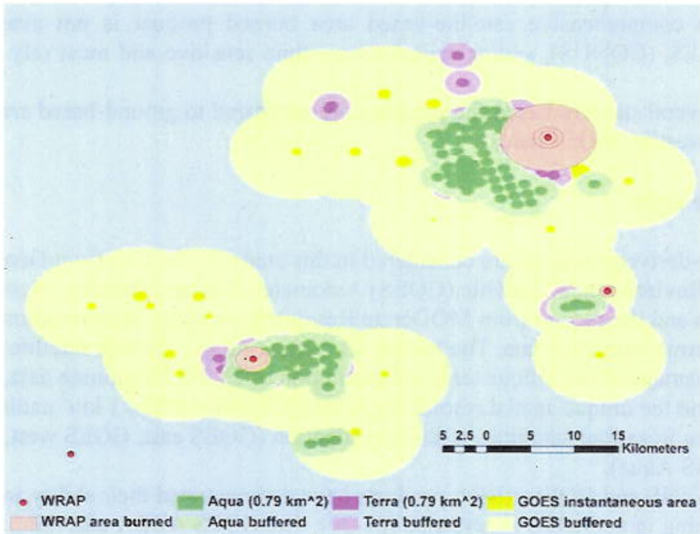


Fig. 2. Buffer overlap. WRAP fire locations are pictured in red, and WRAP area burned data are shown in rose, emanating from the point of ignition. For this reason, satellite data, particularly MODIS, better define the actual shape of fire scars (see Fig. 3.); the buffered Terra and Aqua data often overlap, highlighting the scared region. Note the varying sizes of GOES instantaneous fire size (dark wheat) and the buffers surrounding these regions, both shown in hues of wheat. As long as one buffer touches another and the dates are coincident, then the fire event is considered coincident. In this view, if the satellite dates are within the WRAP date range, then there are three coincident fire events. The WRAP fire in the northeast corner of this figure is defined by more than 1 daily record (concentric rose rings represent daily area burned reported from the point of ignition by the USFS).

Point Response Function (PRF) of the instrument [31]; (3) satellite geolocation error; and (4) spatial error in the ground-based data (buffer example, see Fig. 2) [21-22, 24-25, 28-30]. The buffered regions are used only to establish coincidence in fire events, not to calculate area burned. This provides for a realistic temporal and spatial assessment of the coincidence in ground-based GOES ABBA fire data.

Historic MODIS data are provided by the MODIS Rapid Response System. Two MODIS instruments recorded fire data from the Aqua (available in July 2002) and Terra satellites in 2002. The Rapid Response team used the MODIS Land Rapid Response algorithm to produce datasets that contain latitude and longitude point locations, dates, detection confidence and other ancillary information. Data that have a detection confidence of less than 20% are excluded from this analysis. An area burned estimate is not included in these data; yet a fire is detected within the detectable space, which is in consideration of the resolution and PRF of the instrument [23, 26, 30-31]. For this reason and in consideration of the instruments 1 km^2 nadir spatial resolution, the MODIS data points are surrounded with a 0.5 km radius in GIS. Then, to account for the PRF and inconsistencies in ground-based data, this region is buffered with an additional 3.0 km radius [31]. Similar to the GOES data, these buffered regions are used only to establish coincidence in fire events, not to calculate area burned.

2.2 Ground-based fire data

The Western Regional Air Partnership (WRAP) provided the ground-based "truth" fire data. The WRAP data include natural and prescribed burns and are collected from every available local, state and federal fire data source [209 reports, Departments of Environmental Quality, National Park Service (SACS/1202), etc.]. These data were checked, geolocated, and quality-control reviewed by Air Sciences Inc. in preparation for the intensive 2002 EPA NEI (http://www.wrapair.org/) [32]. The fire data include 5 categories: wildfire; wildland fire use; prescribed burning in wildlands; non-federal rangeland fires; and agricultural burning.

The 2002 ground-based inventory data are the best available and most complete ground-based data, to date, in the U.S. because of the intensive focus by the EPA and RPOs on a "baseline" assessment year. These ground-based data are unique in that an effort was made to include not only the large fires reported on public lands but also to include small fires burned on public lands, anthropogenic pile burning, agricultural and non-federal rangeland fires and burning on private lands. Burning on tribal lands was not typically reported unless there was a coincidence federal report, and additional data was omitted because it did not meet quality control or activity criteria [location, time (start and end date or duration and season), non-zero size, fuel type]. This amounts to omissions of 2.7% for wildfires and 8.8% for prescribed fires. In phase II of this inventory, duplications, primarily due to multiple fires becoming large complexes, were deleted. Also, the unburned island area (uncharred regions within fire perimeters) from the largest 28 wildfires was deleted, which resulted in a 5% decrease in the emissions inventory area.

Even though these data are the most comprehensive and reliable ground-based dataset generated for the U.S., caution is advised when using these data. For instance, agricultural fires do not consistently burn within the space and time reported (i.e. often reported at county level or town center on a monthly timescale), and this is dependent on the reporting state or county. Additional anomalies include: Nevada reported that there was no agricultural burning data available; Washington sent a 2003 database that was considered to be representative of 2002; Arizona and North Dakota accepted the WRAP 2018 Base Smoke Management Scenario; and Montana and South Dakota reported less than 50 acres (0.20 km^2) burned in 2002. Also, while the amount of area burned in non-federal rangelands is considered correct, the temporal and spatial domains recorded are incorrect. Non-federal rangeland burning was pro-rated to the county level using acres of rangeland present in each county, and the monthly temporal resolution was supplied by the Fire Emissions Joint Forum. Hence, non-federal rangelands are suitable for area burned analyses but not for spatial coincidence analyses. Even though these fire types are problematic, they are not ignored in these analyses because rangeland and agricultural fires are significant to air quality and the agencies that use the NEI for management and policy setting. For instance, from October through April, small and prescribed fires account for the majority of fire emissions from the western U.S. [33]. Additionally, in Arizona (in August in September), there is only one recorded agricultural fire, however non-federal rangeland burning accounts for 45% of the total area burned within that 2 month period. For a thorough analysis, these data can not be ignored.

Consequently, the WRAP data are used herein as a standard of comparison because these data are the best conventionally derived ground-based data against which to compare the remotely sensed data. Even though these data have been vetted and corrected, the WRAP data are not infallible. Nonetheless, because it is time- and cost-prohibitive, there are no future plans for another extensive and complete ground-based fire inventory like that produced in 2002.

The WRAP data are prepared in GIS in a manner similar to the satellite data. The GIS point database is converted to a polygon database, and the area burned around the point location of the fire is equal to the area reported burned. The goal of the fire community is to record the amount of area burned daily at the initial sight of ignition. Therefore, even though a fire may burn 500 km^2 over many weeks, there is only 1 recorded point of ignition (Fig. 2). Satellite data capture fire movement over time. Every dataset (WRAP, GOES and MODIS) is projected to USA Contiguous Albers Equal Area Conic for a consistent analysis. Then, the data are compared to investigate fire coincidence in terms of numbers of fires and area burned.

2.3 Temporal and spatial coincidence

Satellite and ground-based data are compared in space and time for coincidence. WRAP data are generally considered "truth" in this analysis, so the question is what percentage (number and area) of the ground-based fires can be identified using satellite data. Based on lessons learned in previous analyses [18, 19], the definition of coincidence has been expanded to better represent reality. For instance, several agencies do not report fires that burn < 100 acres (0.40 km^2) in a day, however satellites often detect this burning. Also, agencies report area burned at the ignition location of the fire, and satellite data detect fire as it moves over space and time (Fig. 3).

For these reasons, a fire is considered coincident if:

- the WRAP and buffered satellite data coincide in space and time; or
- the WRAP data and overlapping satellite buffered space coincide in space and time (Fig. 2 and 3) (to compensate for ground data reporting at ignition site and satellite detections that coincide with the actual movement of the fire); or
- the WRAP and satellite data are coincident in space, as defined above, and the satellite data fall within the date range of the WRAP data [to compensate for days fires are not reported but continue to burn (< 0.40 km^2)]; or
- the WRAP and satellite data are coincident in space, as defined above, and the satellite data fall within 5 days of the beginning or end of the date range of a WRAP fire event [to compensate for days fires are not reported but burn (i.e. < 0.40 km^2)].

Additionally, if multiple ground-based fires are spatially and temporally coincident with one satellite detection, then this detection area will be distributed equally between the multiple WRAP fires.

The coincidence in ground-based WRAP fire events and the events sensed by each satellite (GOES, Terra and Aqua) is evaluated. Then, the coincidence between the WRAP fire events and any satellite (no duplication) is assessed.

2.4 Methodology to estimate area burned in Near-Real-Time (NRT)

Lastly, based on lessons learned during this project and lengthy discussions between agencies, a methodology is conceived and verified using the WRAP data presented in this manuscript. Both the medium-resolution polar orbiters (MODIS) and large-scale geostationary orbiters (GOES) provide valuable fire information that is essential to building the NEI. Consequently, this methodology takes advantage of both types of data and is mindful of the limitations of the satellite data. Because the specific methodology is dependent on this analysis, a full description is provided in section 3.4 of this manuscript. The overreaching goal of this analysis is to demonstrate the viability of both types of satellite data.

Then in section 3.5, several satellite-based area burned products and WRAP ground-based data are inter-compared at a larger scale that includes annual estimates of area burned for 13 WRAP states.

3 RESULTS AND DISCUSSION

In general, each of the satellite instruments is able to capture a large portion of the representative area burned and the spatial domain of the fires. The spatial domain of a fire is captured by satellites as a fire burns and moves over time, and this information is not recorded in current ground-based data. Representative area is the area reported burned in the WRAP data for each fire a satellite identifies. The combined satellite data capture 77% of the representative area burned in Arizona and 98% of the representative area burned in Oregon, as described in detail below. The evidence provided in this investigation demonstrates all the satellites competently identify large fire events, but the relationship is not as strong for

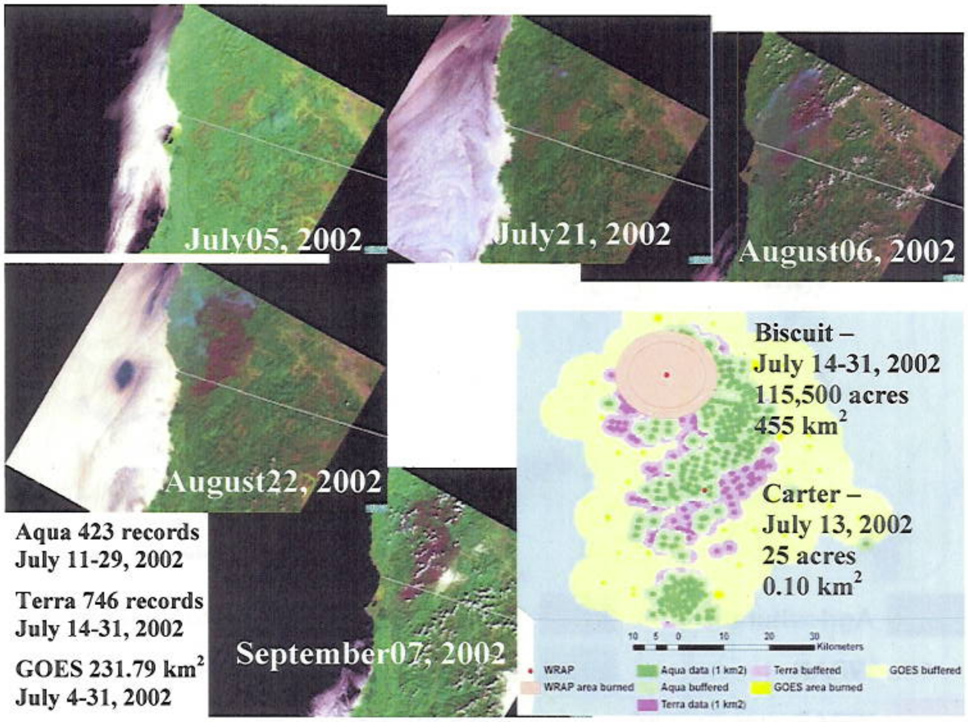


Fig. 3. Evolution of the Biscuit fire over time. Enhanced Thematic Mapper imagery show the shape of the fire scar, which is emulated by the MODIS and GOES satellite data. Note the MODIS data are able to exclude large unburned islands. In this figure, satellite and WRAP fire records represent only those recorded in July 2002, not the entire area burned during the Biscuit fire. In the ground data, area burned in the Biscuit fire was first reported on July 14th, however the satellite data capture the fire before any area is reported burned in the ground data (10 days earlier with GOES data).

smaller fires. Additionally, MODIS detections are more likely to capture the spatial domain of medium to large fires, and GOES data are more likely to detect small, short-lived agricultural fires that are often burning when the MODIS instruments are not overhead.

3.1 Oregon analysis

Statistics are provided in Table 1, and Fig. 4 shows the overall spatial coincidence of the fires that burned in July, 2002. GOES data are able to detect 41% of the number of non-agricultural fires and 37% of the coincident area burned. MODIS instruments aboard Terra and Aqua are able to detect 38 and 48% of the number of non-agricultural fires, respectively. However if one assumes a fire detection is equivalent to 1 km^2, Terra and Aqua detect 134 and 95% of the coincident area burned by these fires, respectively. This highlights the problem encountered if one includes every detection and assumes every detection burns 1 km^2, often double counting. In this case, the total area burned would be 2.3 times greater than the reported burned area. Including both Terra and Aqua instruments is essential for complete fire inclusion due to the distinct overpass times, 10:30 am and 1:30 pm, respectively, and these instruments often sense unique fires. However, simplistic assumptions can lead to over- and under-estimates. A provisional MODIS area burned product has become recently available (http://modis-fire.umd.edu/MCD45A1.asp) [34].

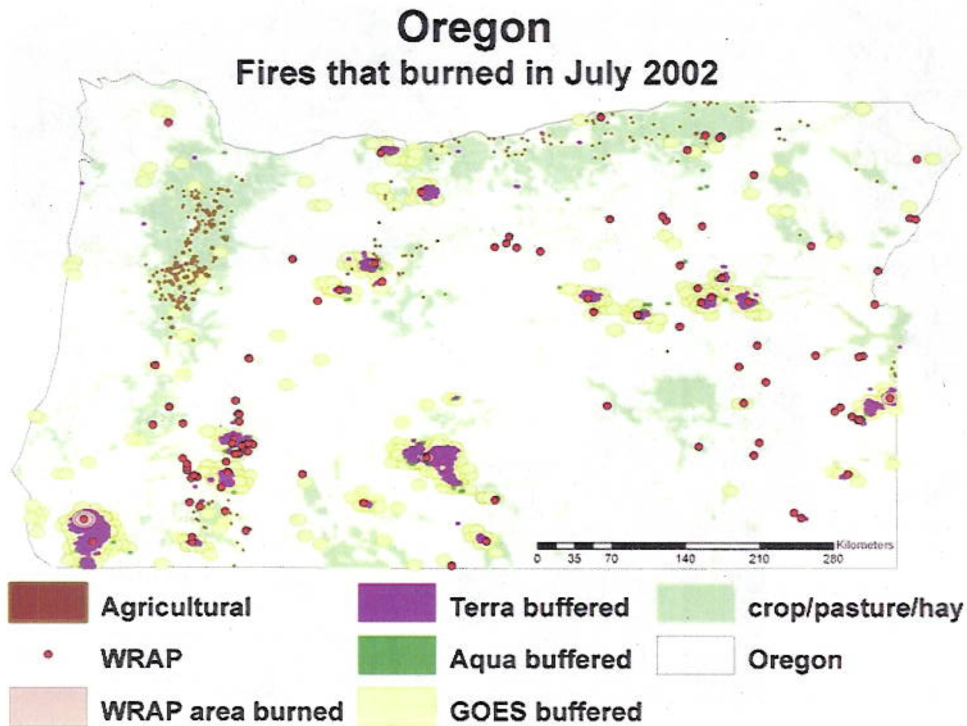


Fig. 4. Geographic coincidence in fire (Oregon July 2002). Note the short-lived agricultural fires that burn on the crop/pasture/hay landscape often coincide with GOES, rather than MODIS data. There are no non-federal rangeland fires burning in Oregon at this time.

GOES is able to detect 34% of the total number of agricultural fires, 20% of the coincident agricultural burned area and 58% of the representative agricultural burned area. Fig. 4 shows agricultural lands, which are dominantly overlaid with GOES, rather than MODIS detections. In contrast, Terra and Aqua detect about 3% of the total number of agricultural fires. Because agricultural burned areas are small, short-lived and often burn when the MODIS instruments are not overhead, particular caution is advised if estimating agricultural burned area with MODIS, however efforts are underway to provide MODIS-based burned area products [34-37]. The reason GOES is able to sense more agricultural fires is related to its geostationary orbit and the instruments ability to continuous view the US, not the resolution of the instruments. MODIS is physically able to detect smaller fires, however the GOES instruments are overhead, detecting fires every 30 minutes, as opposed to the MODIS instruments that have two nadir overpasses each day (more views when considering overlap at higher latitudes).

Overall, Terra and Aqua are able to detect 12 and 14%, respectively of the total coincident number of fires in Oregon in July, 2002. These numbers are low, because agricultural fires are included in this count (312 agricultural out of 413 total fires). Again, making the erroneous assumption of a 1 km^2 burned area per detection, leads to an overestimate of 2.3 times the total reported area (Terra and Aqua, 131 and 94% of the total reported area, respectively). A MODIS burned area product should be able to better quantify area burned in a post-fire analyses, but there is still a need to understand the relationship between fire detection and area burned for NRT use, and this relationship is strongly ecoregion and latitude dependent. GOES captures 36% of the number of all coincident fires and 37% of the total coincident area burned (agricultural area included). It should also be noted that on several occasions, either all satellites or two satellites identified spatially and temporally coincident fires that are not reported in the WRAP, so one might anticipate that the coincident event percentages reported here are lower than the reality due to errors in the ground data.

Coincident fires are compared in Fig. 5 (satellite area to WRAP area), and each satellite instrument correlates well with the WRAP data. These correlations are best when large fires are considered, and the relationship does not hold for small fires, particularly those less than 5 km^2. However if one considers a straight area to area comparison (1:1 line in Fig. 5), each MODIS instrument generally overestimates area burned and substantially overestimates area burned if Terra and Aqua detections are combined, again highlighting the error associated with simply counting every pixel. In contrast, GOES area burned generally underestimates area, because it is a cumulative instantaneous fire size product in this analysis. For instance, every 15 minutes (with 2 satellites), GOES ABBA records the fire size of the area burning at that instant, so there are 14 minutes, minimally, without a record. Depending on the rate of fire spread, the ultimate area burned is influenced. This low bias is known, and there has been a recent effort to integrate these areas over time and scale these data [38-40]. One of the advantages of GOES data is that it provides the temporal information necessary to capture the diurnal cycles that typify fire regimes (e.g. agricultural fires set when humidity high and natural fires active when humidity low). In section 3.4, a GOES-based NESDIS (National Environmental Satellite Data and Information Service) area burned product will be compared with other area burned products.

In combination, all the satellites are able to detect 43% of the total number of fires and 63% of the total number of non-agricultural fires. The combined satellite products are able to detect 98% of the representative area burned compared with ground-based data. This is because the satellites are able to capture the largest fires and this amounts to most of the area burned. For instance, in Oregon, 80% of the area burned can be defined with the largest 10% of the fires. This relationship is consistent in Florida [19], where in the wildfire database, the largest 1% of the fire events account for 75% of the total area burned. In Canada, the largest 2-3% of the fires account for 97-98% of the area burned [41], and in Alaska, the long-term fire records (since 1950) show that 96% of the area burned is by large fires ($> 20\ km^2$) [42]. This relationship is also consistent in Russian ecosystems [43, 44]. Consequently, the largest fires generate the largest amount of emissions, present the greatest health risk to the public, and push the limits of air quality attainment.

From the satellite point of view, 98% of the area detected by all satellites is coincident with the ground-based data. 97% of the GOES data is coincident with the ground-based data; 98% of the Terra data is coincident; and 98% of the Aqua data is coincident.

3.2 Arizona analysis

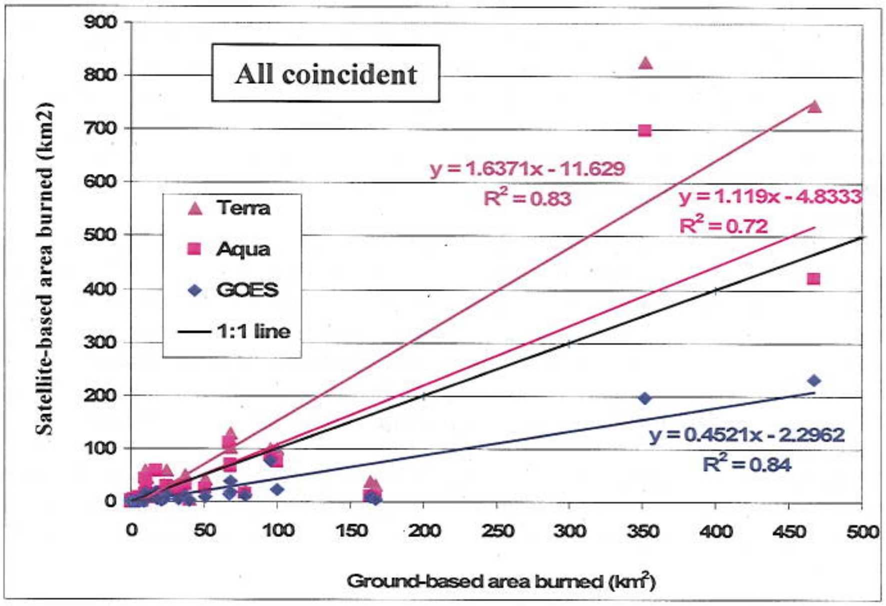
The overall spatial coincidence of the fires that burned in September and August, 2002 is shown in Fig. 6, and the statistics are provided in Table 2. There are distinct differences in Arizona when compared with Oregon. First, the geology, weather and dominant ecosystems inhibit the ability of satellites to detect fire, because the background environment is both hot and reflective. For instance, GOES classified 85% of the fires as low probability flag 5 in Arizona, as compared with GOES data from Oregon that classified 14% of the data as flag 5 low probability. Secondly, there is only one agricultural fire reported during this 2 month time period, yet rangeland fires account for greater than 45% of the total area burned. Because rangeland fires are not accurately recorded in space or time (day inaccurate; month accurate), coincident analysis is impossible for rangelands, but area burned comparisons are possible.

When comparing coincidence (non-federal rangelands excluded), GOES identifies 9% of the total number of fires and 32% of the total area burned. Terra and Aqua identify 26 and

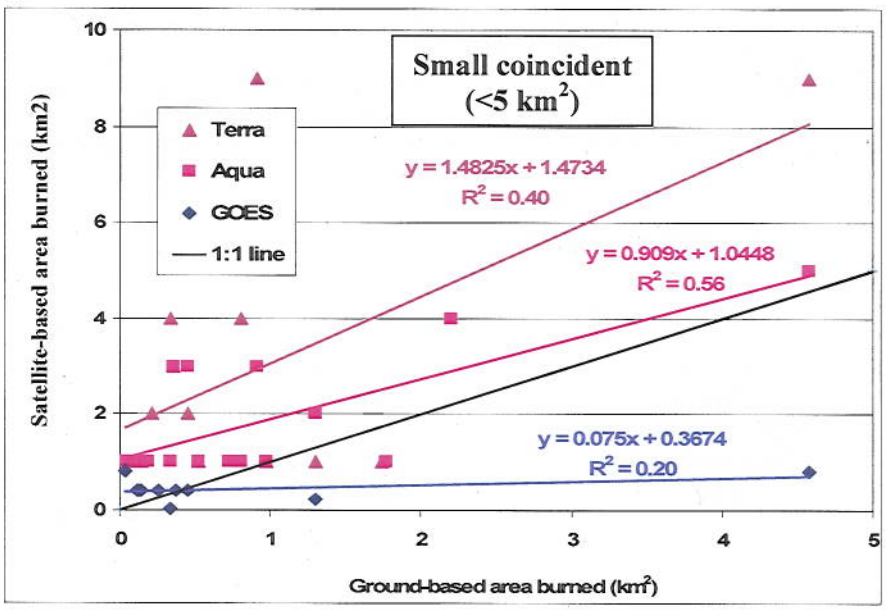
Table 1. Oregon fire statistics for July 2002. GOES area data are the aggregate of coincident instantaneous fire size, and MODIS data assume 1 detection is equivalent to 1 km^2. This table highlights the overestimates that result if one assumes every MODIS detection equates to 1 km^2 burned. Representative area is the area reported burned in the WRAP data for every fire a satellite identifies. Without duplicates evaluates coincidence with all satellites, and duplicate coincidence (i.e. GOES and Terra identify the same fire) is ignored. The first Aqua record is recorded on July 04, 2002 (instrument newly launched).

All data, not solely coincident data			
Data source	Number records or detections	Area burned or MODIS detection equivalent	% total area burned
GOES ABBA	1996	800 km^2 197,684 acres	38%
MODIS Terra	2761	682,258 acres	131%
MODIS Aqua	1984	490,257 acres	94%
Oregon ground fire data	101 fires, 296 records (without agriculture)	Total 2113 km^2 (522,124 acres); without agriculture 2026 km^2 (500,554 acres), mean 1691 acres, range 2 - 54,401	
Agricultural fires	312	agriculture, 87 km^2 (21,569 acres), mean 69 acres, range 0.3 – 469	

Coincidence analyses (black excludes fire in agricultural lands and red includes fire in agricultural lands)				
Data source	Number records coincident	All area burned or MODIS detection equivalent	% area coincident with satellite data	% number of ground fires coincident with satellite data
GOES ABBA wildfires [plus agric.]	41 [148]	756 km^2 (186,735 acres); [97% GOES data coincide with ground data and agricultural lands.]	37% [37%]	41% [36%]
MODIS Terra wildfires [plus agric.]	38 [49]	2706 detect (668,667 acres); [98% of Terra detections coincide with ground data and agricultural lands]	134% [128%]	38% [12%]
MODIS Aqua wildfires [plus agric.]	48 [57]	1930 detect (476,913 acres); [98% of Aqua detections coincide with ground data and agricultural lands.]	95% [92%]	48% [14%]
All satellite	64 [179] (without duplicates)		**Representative area 98%**	63% [43%] (without duplicates)



A.



B.

Fig. 5. Comparison of coincident satellite and ground-based area burned data for Oregon, July 2002. All coincident fire data show good correlation, however the relationship is weak for small fires. Additionally one must note the differences in the axes. Even though "all" data correlate well, GOES data underestimate area burned, and the 1 km^2 MODIS detection assumption leads to a substantial overestimate of area burned, particularly if both Terra and Aqua data are utilized. Exploiting Terra and Aqua is advantageous because of their unique overpass times, which identify different or continuously burning fires; however, the 1 km^2 assumption leads to erroneous results. The temporal ability of GOES is one advantage of this instrument.

21% of the total number of fires, respectively. In this unforgiving region, assuming every MODIS detection equates to 1 km^2 results in estimates of 100 and 97% from each instrument and a combined estimate almost 2 times greater than the total reported area burned. Of the fires that are coincident in the satellite and WRAP data, these correlate well, as shown in Fig. 7. In general, large fires correlate better with satellite data than small fires, and the relationship breaks down for fires less than 5 km^2. As expected, GOES ABBA generally underestimates total area burned, because it is a product derived from cumulative instantaneous fire sizes.

All satellites combined are able to detect 32% of the total number of fires that burned in this region. The total representative area burned by all satellite data is 77% (non-federal rangelands excluded). Non-federal rangelands represent a large portion (45%) of the total area burned, but these fires are not coincident in space and time, so they are not part of the coincident representative area. The satellites are able to capture the largest fires in Arizona and as previously stated, this accounts for most of the area burned (77%) and biomass emissions. Specifically for Arizona, the largest 10% of the fires represent 74% of the total area burned.

If we consider the satellite point of view, 76% of the GOES area is coincident with the ground-based data; 84% of the Terra data are coincident; 80% of Aqua data are coincident; and 82% of the area detected by all satellites is coincident with the ground-based data.

3.3 Limitations of the satellite data

To fully comprehend results, we must view these within the context of the limitations of both the satellite and ground-based validation data. For instance, cloud cover inhibits the instruments ability to detect active fires, so when thick persistent clouds are overhead, active fires are missed. Then again, the weather that is conducive for natural fires (dry, high pressure dominated) is often not conducive for persistent cloud cover (low pressure). Additionally,

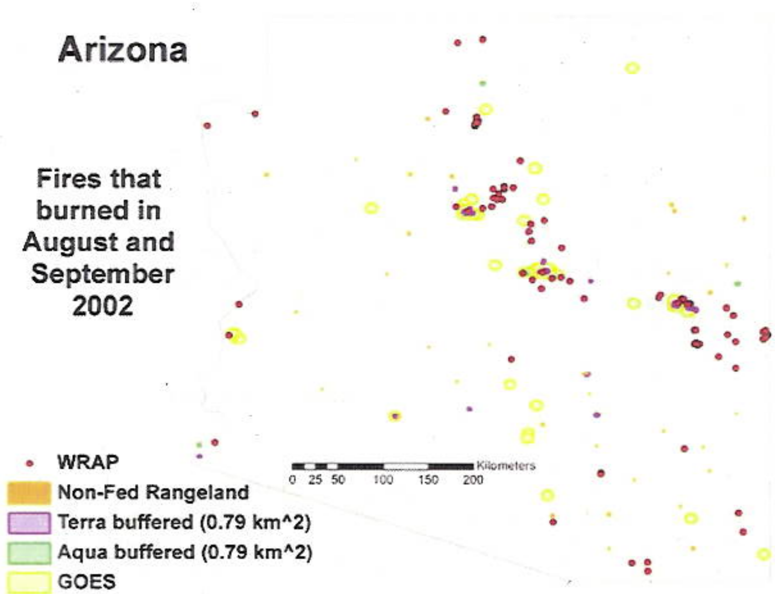
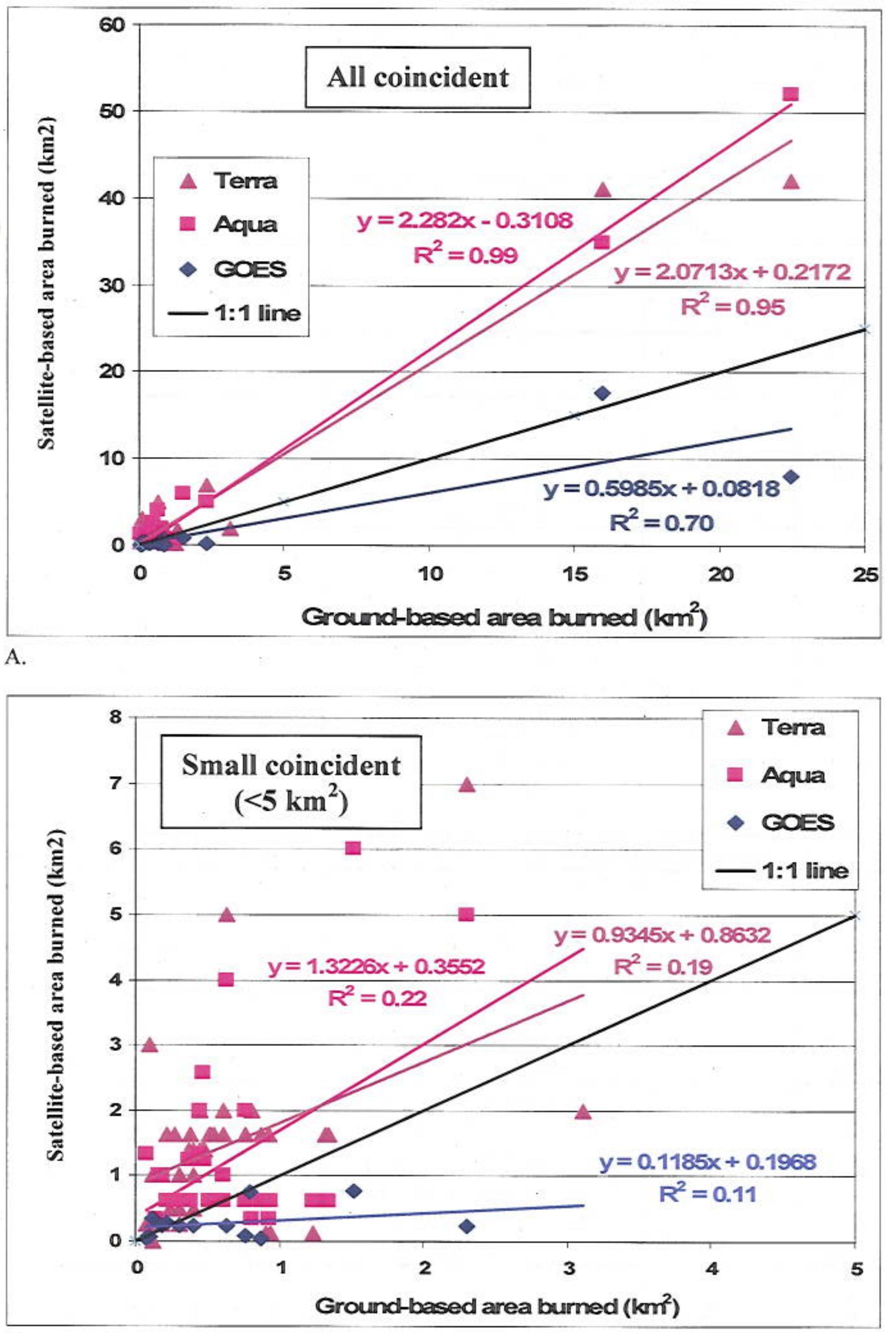


Fig 6. Geographic fire coincidence (Arizona August and September, 2002). Rangeland fires are distributed randomly over rangelands and are not considered geographically accurate, however area burned is accurate at a monthly timescale.



A.

B.

Fig. 7. Comparison of coincident satellite and ground-based area burned data for Arizona (August and September 2002). All coincident fire data show good correlation, however the correlation for small fires is weak. Even though "all" data correlate well, GOES data underestimates area burned, and the erroneous 1 km^2 MODIS detection assumption leads to substantial overestimates of area burned.

Table 2. Arizona fire statistics for August and September, 2002. GOES area data are the aggregate of coincident instantaneous fire size, and MODIS data assume 1 detection is equivalent to 1 km^2. Assuming every MODIS detection equates to 1 km^2 results in a 197% overestimate in this region. Representative area is the area reported burned in the WRAP data for each fire a satellite identifies. Without duplicates evaluates coincidence with all satellites, and duplicate coincidence (i.e. GOES and Terra identify the same fire) is ignored.

All data, not solely coincident data (includes non-federal rangelands)				
Data source	Number of records or detections	Area burned or MODIS detection equivalent	% total area burned	
GOES ABBA	169	38 km^2 9491 acres	23%	
MODIS Terra	168 detections	41,514 acres	100%	
MODIS Aqua	162 detections	40,031 acres	97%	
Arizona ground fire data	165 fires, 201 records (without rangelands)	Total 167 km^2 (41,366 acres); without rangeland below 92 km^2 (22613 acres), mean 113 acres, Range 0.5 – 1598		
Non-federal rangeland	34	76 km^2 (18,750 acres), mean 552 acres, Range 124 – 1100		
Coincidence analyses (without non-federal rangelands)				
Data source	Number records coincident	Area burned or MODIS detection equivalent	% area coincident with satellite data	% number of ground fires coincident with satellite data
GOES ABBA	15	29 km^2; 7213 acres; 76% of GOES data coincide with ground data	32%	9%
MODIS Terra	42	141 detections; 34,903 acres; 84% of Terra detections Coincide with ground data	154%	26%
MODIS Aqua	35	130 detections; 31,876 acres; 80% of Aqua detections coincide with ground data	140%	21%
All satellite	53 (without duplicates)		**Representative area 77%**	32% (without duplicates)

each instrument is limited in its ability to detect and geolocate fire by its spatial resolution (GOES 16 km^2; MODIS 1 km^2). For example, when an instrument detects fire, the position of the fire within a pixel (or outside the pixel) is unknown. Concurrently, the Point Response Function (PRF) of the instrument, which is the actual footprint of the instrument, restricts the ability of an instrument to detect and geolocate a fire [(~ 80% of the energy from the ground is sensed over a distance of 2.84 km (MODIS) and 11.36 km (GOES), for ~99% of the energy this distance increases to 4.94 km (MODIS)][31, 45]. The result of the intentional PRF instrument design is that a complete picture of the surface is captured (an intentionally engineered data smear), yet one hot fire that has a fire line much less than 1 km^2 (perhaps 50 x 250 m or 0.0125 km^2) can often activate numerous MODIS 1 km^2 fire detections. Theoretically, 1 km^2 resolution sensors can detect fires as small as 10 x 10 meters [46], however Giglio et al. [47] described fire detection within an "envelope of detection probabilities", dependent on atmospheric conditions, flame intensity, fire size, background temperature and reflectance, scan angles and instrument capabilities. Interestingly, it was the unintentional detection of gas flares that led to our discovery of the ability of satellites to detect fire [48-51]. Another consideration is instrument orbit. MODIS instruments reside in sun-synchronous orbits, and each instrument nominally provides one daytime and one nighttime overpass per day (2 satellites Aqua and Terra, 4 overpasses with some latitude-dependent edge overlap). Consequently, fires that burn between satellite overpasses are excluded.

Even though the GOES instruments have a larger spatial resolution, the instruments capture a greater number of small agricultural fires. This seems a bit counterintuitive until one remembers the GOES instruments are in a geostationary orbit and are constantly viewing North America, enabling the instruments to sense fires every 15 minutes (2 instruments, each 30 minutes). However, the geolocation of a GOES fire event could be off by a maximum of about 10 km (0.05 degrees) from the center of the pixel due to its PRF, nadir spatial resolution, geolocation accuracy, and the position of a fire within a pixel [45].

Each satellite has limitations and strengths, and it is the goal of this work to describe and define limitations but also to highlight the value of satellite data. Satellite data are able to identify fires in NRT, often providing early warning to fire management organizations; satellites identify fires that are not reported with consistency and without regard to political or geographic boundaries; and satellites are able to quickly identify fires so regions that may experience health risks can be notified. Each of the instruments sense fires that the other instruments do not, but generally, they capture the same fires and occasionally all instruments capture fires that are not described in the ground fire datasets.

3.4 Potential satellite-based area burned available in Near-Real-Time

As shown in Fig. 5 through 7, area from each satellite instrument correlates well with coincident data and adds temporal and spatial information that is not available from other sources. However, estimating area burned using satellite data presents challenges. One conundrum is that to accurately capture all fires, one must use all the instruments. Terra and Aqua capture distinct or continuing fires because they have unique overpass times, separated by roughly 3 hours, and GOES also captures these fires, as well as small agricultural fires that are not burning during MODIS overpass times. However, simply combining the instruments does not result in an accurate estimate of area burned.

To address this problem using lessons learned from this and previous work [14, 18-20], we generated a cumulative satellite product that takes input from Terra, Aqua and GOES. Using a linear regression approach, Giglio et al. [52] concluded that one Terra detection in the North American temperate ecoregion equates to about 0.84 km^2, however we intend to include both the morning and afternoon MODIS overpasses, so we want to ensure that we avoid duplication or double counting of areas burned. First, Terra and Aqua fire locations are buffered with a 0.50 km diameter, and the area of this buffered space is equal to 0.79 km^2. The buffered MODIS locations are then combined into one aggregated MODIS data product, eliminating detection overlap (i.e., the union of buffered MODIS area). An example of the resulting product is shown in Fig. 8. Comparing this result from the Biscuit fire (July 2002 burning only) to that shown in Fig. 3 illustrates the improvement in the area burned estimate for this fire. Simply counting MODIS fire detections (and assuming 1km^2) can result in over 2 times the area reported burned, and GOES cumulated area burned estimates only 51% of the area. In contrast, the buffered MODIS area overestimates the area burned in this fire by only 6% (106% of the area). Also, the natural fire perimeter is captured with MODIS data, and this benefit is not available in the point-based ground data.

For Oregon, after buffering, combining and aggregating the MODIS data, the total area burned defined by this product is 87.5% of all the area burned (agricultural and non-agricultural). Remembering that GOES data accurately describes agricultural burning in space and time but only 1/5 of the area burned, the GOES agricultural area burned product is scaled by a factor of 5. This product represents 99.83% of the total area burned by agricultural fires in Oregon in July, 2002. Incorporating both the MODIS and GOES data products results in a satellite-derived fire product that quantifies 92% of the total area burned (agricultural and non-agricultural).

Next, this methodology is used to quantify area burned in the vastly different ecosystem of Arizona. One difference is there are no coincident agricultural fires. However, because a large portion of the area burned is non-federal rangelands, and there is confidence in the season and amount of area burned, this area is necessarily included. The aggregated MODIS product defines 81% of the total area burned in Arizona for August and September. Because fire detections are available in NRT, this methodology lends itself to emissions and pollution forecasting. Paired with a land cover map to identify agricultural land, this is a powerful methodology for estimating fire emissions in NRT.

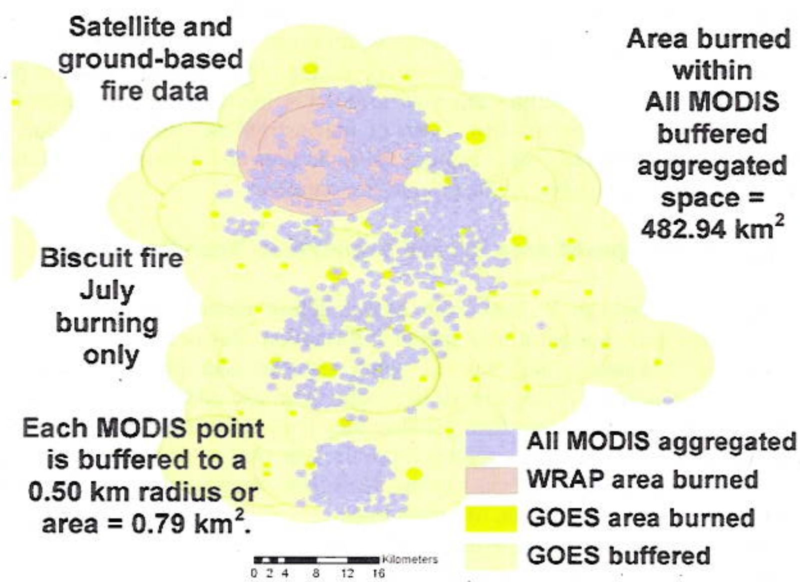


Fig. 8. Buffered and aggregated MODIS (Terra and Aqua) data product. Note the overlap is eliminated from the Terra and Aqua instruments. Total area burned within the buffered space for the Biscuit fire in July is 483 km^2, which is only 6% greater than that reported (455 km^2, see Fig. 3).

In Fig. 9, the all-MODIS/buffered/aggregated product is compared to the coincident WRAP ground-based fire data for Oregon (July 2002) and Arizona (August and September, 2002) to similarly assess this methodology. The all-MODIS NRT Oregon product generated in this study correlates well with the ground data, and this analysis includes both Terra and Aqua MODIS instruments. The all-MODIS NRT Arizona data, derived in this study, correlates well with the ground-based data, and again, all MODIS data are included in this comparison. Still, in both the Arizona and Oregon cases, the correlation is strongly controlled by the larger areas burned and the correlative relationship breaks down at about 5 km^2.

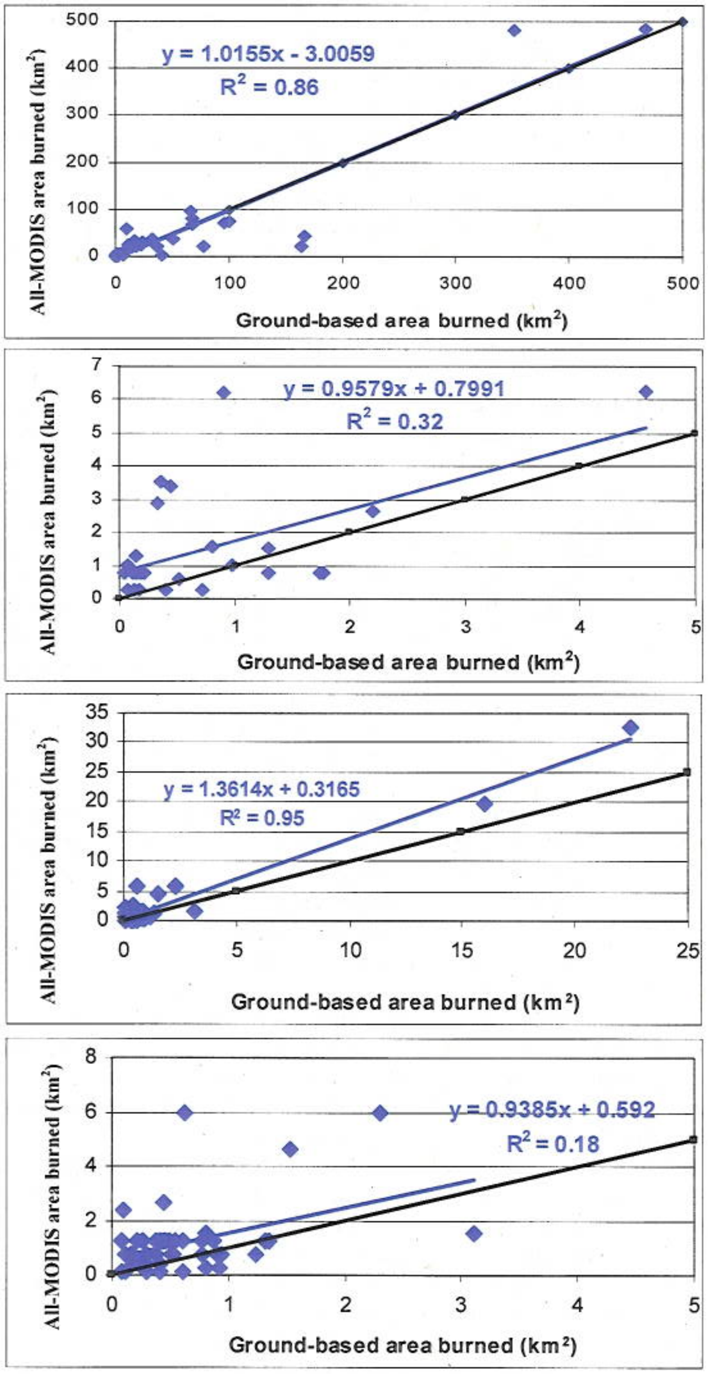
This quickly derived NRT product serves as an example of the possibility of combining multiple satellites.

3.5 Inter-comparison of area burned data products for the WRAP region

There are several projects underway that are attempting to estimate and improve area burned and emissions estimates from biomass burning within CONUS. In Fig. 10 and 11, area burned from several of these projects is compared to ground-based data from 13 western states, and Fig. 12 shows the type of burning reported. GFED (version 2.1) is a global MODIS-based product that calculates area burned based on fire scars and active fire detections [15, 16, 42, 53]. The NESDIS product is generated using GOES data that incorporates potential burning between detections based on the diurnal fire cycle [38, 39, 54]. The NCAR regional product is MODIS-based and scales active fire detections based on the ecosystem and the percent of the pixel that is vegetated [13]. The USFS AirFire Team and STI developed the SMARTFIRE product using NOAA's fire Hazard Mapping System (HMS) data, which incorporates MODIS, GOES and Advanced Very High Resolution Radiometer (AVHRR) imagery. SMARTFIRE is continuously evolving in communication with the EPA and the Pacific Northwest Forest Service, however its initial development is based on this research [55-56]. This version of SMARTFIRE excludes agricultural lands, which are masked using the Fuelbed Characteristic Classification System (FCCS) data. Realtime Air Quality Modeling System (RAQMS) is a global- to regional-scale chemical transport model that generates an area burned product using MODIS active fire detections [54, 57-58]. "This study" uses all-MODIS data only, excluding GOES data, for this particular analysis. This is not a complete list of the area burned products available in the U.S., but the spatial domain of each of these datasets includes CONUS; these products are generally available; and they each offer a unique perspective for calculating area burned.

The HMS data are only available for the last five months of 2002, so we evaluated products annually and for the last 5 months of the year. Additionally, Aqua was launched in 2002 and started collecting fire data in July, so several of these products could be influenced by the addition of the Aqua instruments (NCAR, GFED and this study). RAQMS also relies on both MODIS instruments and provided data for the last 6 months of the year.

With one exception (NESDIS for Utah), the WRAP ground-based data are higher than satellite-based estimates by an average of 48% (satellites account for 52%) (Fig. 10). In the mean, GFEDv2.1 accounts for 34% of the 13 WRAP states total area burned for 2002; NCAR accounts for 58%; "this study" accounts for 60%; and NESDIS accounts for 58%. The NESDIS estimate is 6% higher than the WRAP data for Utah, and interestingly, every satellite product is closest to this estimate (71-78% of estimate). Without teasing apart the detail, there are no general patterns that reveal themselves. Depending on the state, NESDIS, NCAR and "this study" are closest to the WRAP estimates. GFED version 3 will be released soon and initial analysis reports larger areas burned. Part of the discrepancy between satellite and ground data could be due to a particular states reporting scheme. For instance, one might expect that the GFED product would be consistently lower for states that had substantial agricultural fires (Fig. 12), however Colorado and Oregon do not report substantial agricultural fires. One might expect that NESDIS would consistently capture agricultural



A. Oregon large fires.

B. Oregon small fires.

C. Arizona large fires.

D. Arizona small fires.

Fig. 9 The all-MODIS/ buffered/aggregated area burned product generated in this study correlates well with the coincident ground-based data from Oregon and Arizona. The difference between these correlations and Fig. 5 and 7 is this analysis includes both the Terra and Aqua data and eliminates overlap. Large areas burned correlate best and the correlative relationship breaks down (< 0.50 r^2) for areas < 5 km^2. 1:1 lines are shown in black.

burning, however North Dakota (ND) is the exception. It is possible agricultural area in the ND WRAP is high but to validate this idea would require a monthly analysis.

Notably, agricultural and non-federal rangeland burning does account for a significant amount of area burned and emissions from the western U.S., and the type, size and timing of fire does influence an instruments ability to detect fire. Another source of potential error in the ground data is the reporting methodology on federal lands, which is typically from fire perimeters that include unburned islands that the satellites would not sense as burned. The size of these unburned islands is an average of 24% for the largest fires (± 17% SD), however the WRAP data have been corrected for the largest area burned discrepancies [32].

For these reasons, we also consider the last five months of 2002 (Fig. 11), which also allows for two additional products. However, with the exception of August, the primary natural fire season has passed, which also influences the types and sizes of fires burning and analysis. In the mean, for the last 5 months of 2002 in the 13 WRAP states, GFEDv2.1 accounts for 32% of the total area burned; NCAR accounts for 67%; "this study" accounts for 69%; NESDIS accounts for 47%; SMARTFIRE accounts for 52%; and RAQMS accounts for 74%. Again, without a detailed state by month by category assessment, it is difficult to identify general patterns. Depending on the state, NCAR, RAQMS, "this study" and SMARTFIRE are each closest to the WRAP estimate.

Each product is uniquely able to capture different types of fires, and without a detailed assessment (by state and category), it is impossible to tease apart the error associated with particular satellite products and types of fires (small agricultural or prescribed burning or medium to larger non-federal rangeland or wildfires) or general error in state reporting. This type of analysis is out of the scope of this work, however we highlight the need for a more complete assessment, in essence stepping back to move forward. The main objective of this type of detailed investigation would be to move us all forward by sharing information and understanding the strongest and weakest characteristics of our area burned algorithms. Even though area burned is only one source of error in emission estimates, it can be a large source of error.

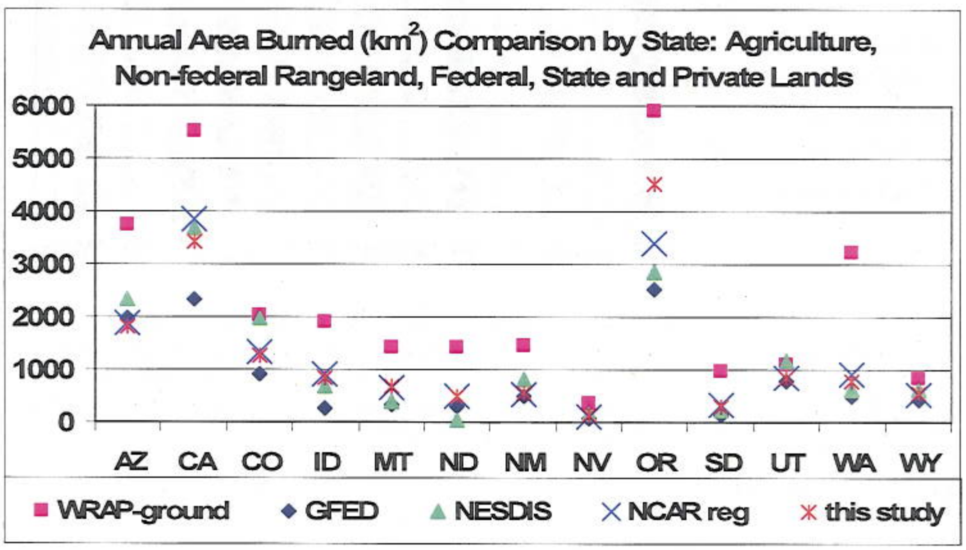


Fig. 10 Annual area burned in each of 13 WRAP states for 2002. WRAP is the ground-based report and the other estimates are satellite-based. Aqua MODIS started recording fire detection in July 2002, which could have influenced GFED and "this study" and would have influenced NCAR regional.

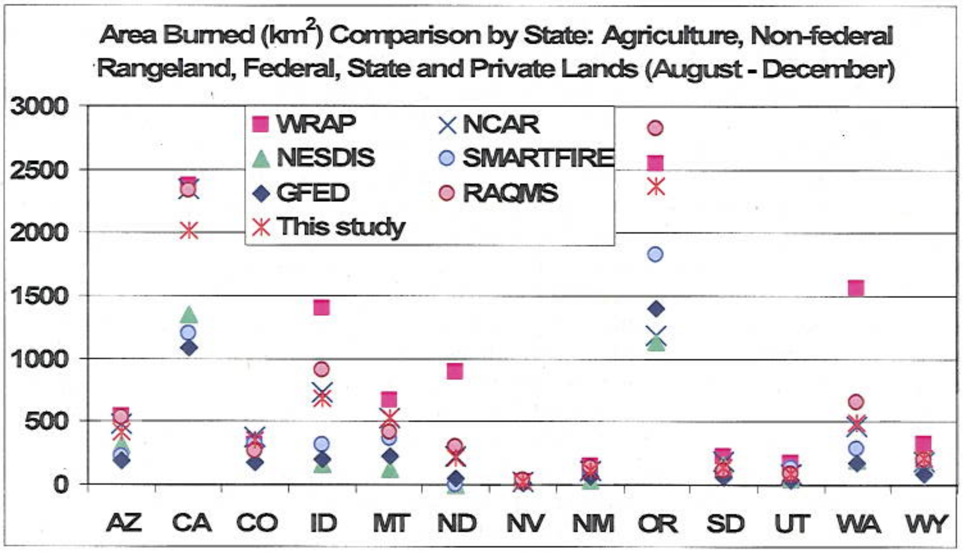


Fig. 11 Area burned from August through December of 2002 in 13 WRAP states. With the exception of August, these months are outside of the primary natural fire season, however several additional products are available after July 2002 following Aqua's data availability.

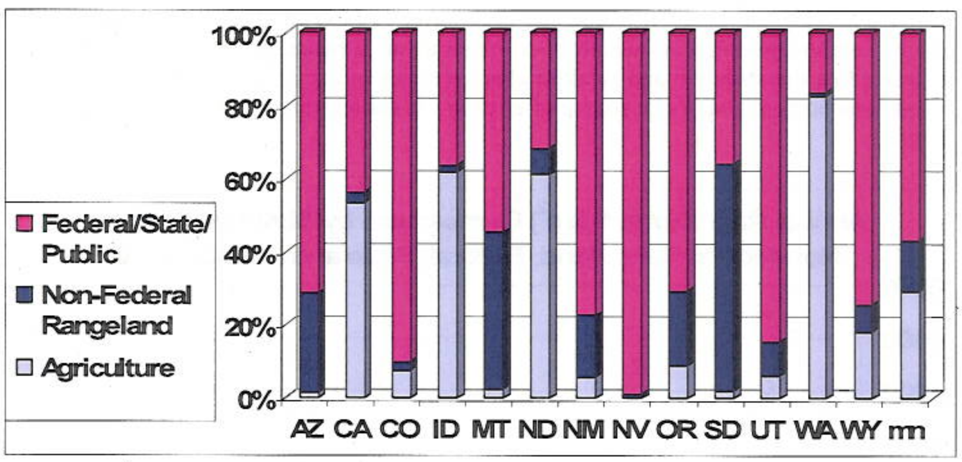


Fig. 12 Percent area burned from each category in individual WRAP states for 2002. One might expect agricultural fires to be smaller, short-lived and to generally burn outside of the primary "natural" fire season. The WRAP relied on the states to accurately report area burned in agricultural and non-federal rangelands, and some states have mandates and more experience reporting these areas (see section 2.2). The last value on the x-axis is the mean (mn) of all the reporting states.

4 CONCLUSIONS

This investigation focuses on defining the error associated with one major parameter necessary to estimate biomass burning emissions, area burned. First, we concentrate on two distinct ecoregions in Arizona and Oregon to quantify the amount of area burned and numbers of fires that can be defined by satellite data. Each of the satellites is able to distinguish the largest fires in both ecoregions, which accounts for most of the area burned. The combined satellite data [GOES area burned (cumulative coincident fire sizes) and Terra and Aqua detections] are able to identify 98% of the representative coincident area burned in Oregon and 77% of the representative coincident area burned in Arizona. In terms of numbers of fires, the satellites are spatially and temporally coincident with 63% of the total number of fires in the Oregon ground-based data (43% if agricultural lands included) and 32% of the number of fires in Arizona. However, if one makes the flawed assumption of including all MODIS (Terra and Aqua) detections and equating each to 1 km^2 burned, that could result in overestimates greater than 2 times the WRAP ground data. GOES area burned estimates between 23–38% of the total WRAP area burned.

When considering the satellite perspective, 98% of the area detected by all satellites is coincident with the ground-based data in Oregon, and 82% of the satellite area is coincident with the ground data in Arizona. Each of the satellite instruments accurately defines the spatial pattern of fire as it moves across a landscape, which is information that is not available in current ground-based data. In spite of its large-scale spatial resolution, GOES demonstrates an enhanced ability to detect small agricultural fires, which is a result of its geostationary orbit and continuous views from space.

Based on the results of these analyses and several over the last couple years, a satellite-based area burned product is developed using all three satellites. MODIS data (Terra and Aqua) are buffered (0.50 km diameter) to 0.79 km^2, combined and aggregated to eliminate pixel area overlap. Then, GOES data are adjusted (by a factor of 5) to quantify area burned in agricultural regions. Incorporating both the MODIS and GOES data results in a satellite-derived fire product that quantifies 92% of the total area burned in Oregon, which includes agricultural and non-agricultural fires. In Arizona, the aggregated MODIS product defines 81% of the total area burned, which includes non-federal rangelands. The derived product is produced with satellite data that are available in NRT, therefore this methodology could be used to estimate biomass emissions in a forecasting mode and to warn the public of a potential air quality health risk.

Lastly, multiple satellite-based area burned products are compared for 13 WRAP states during 2002. WRAP ground-based estimates are typically larger than all the diverse satellite-based products by a mean of 45% (satellites account for a mean of 55%), and no consistent patterns emerge from this brief comparison. However, the comparison supports the notion that each product has unique capabilities and clarifying these characteristics would be a fruitful endeavor.

In the pinnacle year of analysis, 2002, the EPA motivated the generation of a rigorous ground-truth area burned dataset to establish baseline year emissions, which was costly and took years to prepare (2002 finalized in 2007). However, even this type of data can miss and misplace (spatially and temporally) some fires, and area burned is necessarily determined after the fact. In addition, most ground-based data are not of 2002 quality and will not be in the future. Although satellite data are not able to fully characterize the detail desired by the EPA (i.e. time a fire starts and ends, precise area burned on a small scale), it has a number of advantages. Satellite data can identify fire in a timely manner, which serves the EPA by enhancing the ability of the EPA to notify the public of an imminent fire-induced health risk, and in quantifying and defining where smoke originates, satellite data can provide clarity in exceptional events for use in the Exceptional Events Rule. Moreover, satellite data accurately define fire perimeters as they progress across a landscape, and source location is essential for accurate modeling of the transport of biomass burning emissions. Considering that firefighters are generally concerned with controlling fire and protecting human life and property, mapping area burned for emissions is not their highest priority. Satellite data can immediately add enhanced value to fire products. Additionally, accurate emissions estimates can be made available for general use almost immediately using satellite data. Also, because the EPA currently collects ground fire data only once every 3 years, satellite data can be used to estimate emissions in the years where the detailed NEI data are not available. Considering the additional cost of detailed analysis (an extra ~ 1 million dollars, 24-36 months), these are substantial benefits.

The type of analysis presented in this investigation is essential to assigning potential error to satellite-based emissions estimates. Without these data, confidence in resulting emission estimates is limited. We suggest that satellite data could significantly improve biomass burning emission estimates by: (1) improving the temporal availability of emissions; (2) providing spatial information that is not currently available to the NEI; (3) enhancing and improving estimates during times when detailed ground inventories are not available; and (4) enhancing and improving estimates in regions where temporal and/or spatial ground-based data are imprecise.

Motivated by the goals of the NASA Applications Air Quality program, this work evolved from lengthy interactions between the US EPA, RPOs, federal, state and local organizations who all help generate the NEI and are users of the NEI to meet their regulatory and policy needs. These interactions are geared towards first understanding the customer's needs and then offering a tractable and quantifiable solution. The NASA Applications program is a mechanism through which bridges are built between sister federal organizations to enable publicly-funded satellite data to attain its full potential. This process and analysis is cutting edge applications science for the U.S. This research has offered guidance and proof of concept by comparing satellite data to the "trusted" NEI data and process; it provides the clarity and understanding that is essential to move this process forward.

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Chieko Kittaka played an integral and substantial role in every project she touched. Everyone that knew her would agree that as a scientist, Chieko easily accomplished the work of two competent scientists. Her work is her legacy. We miss her and will continually remember her contagious smile.

http://memorialwebsites.legacy.com/Chieko/homepage.aspx

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